New Views on Extrasolar Planetary Systems from *Kepler*

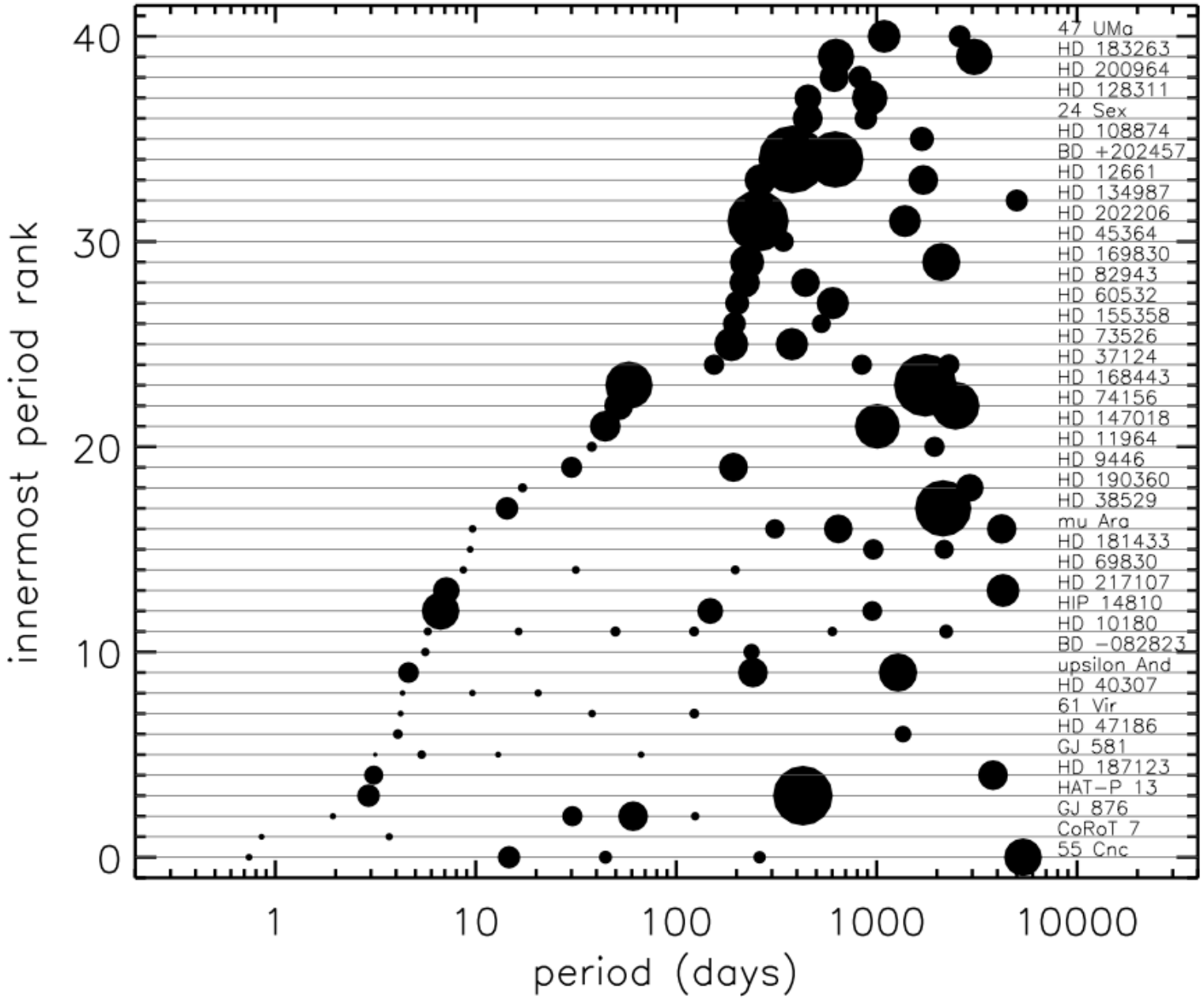
Dan Fabrycky
UC Santa Cruz

Jack Lissauer, Josh Carter,
Matthew Holman, Darin Ragozzine
Jason Rowe, Bill Cochran,
Laurance Doyle, and the *Kepler* team

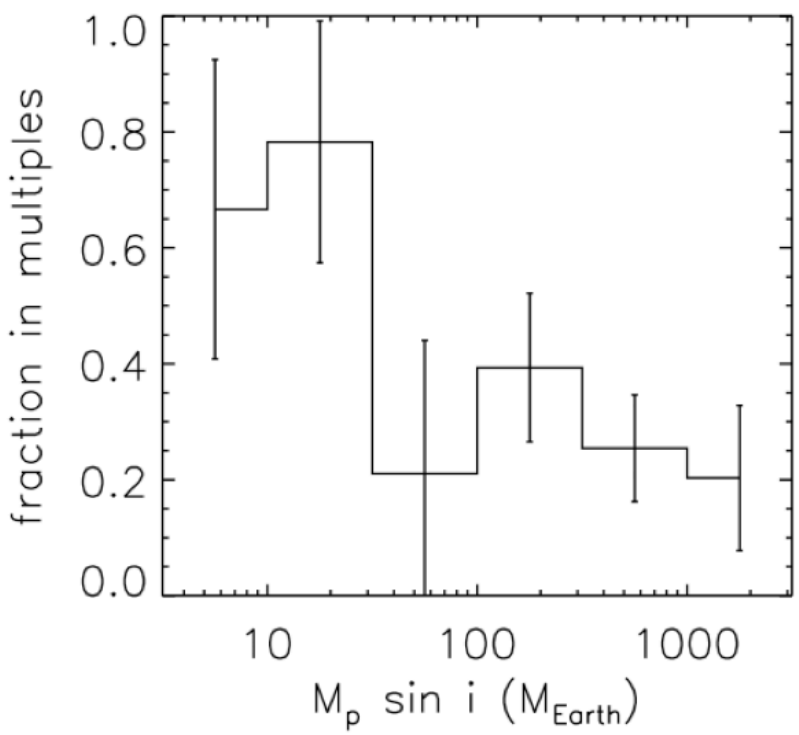
Outline

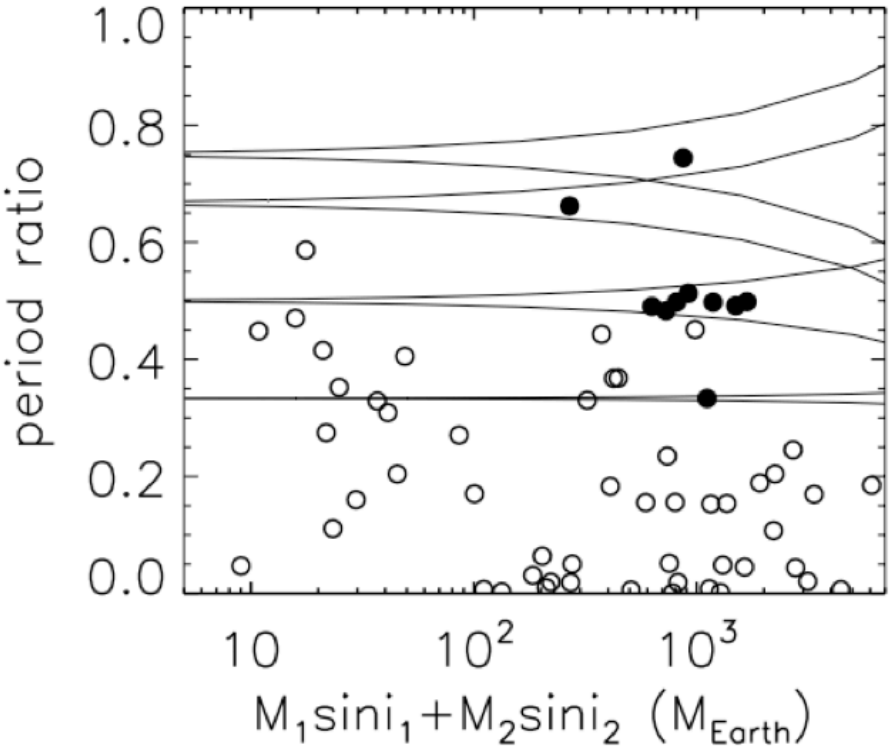
- Exoplanetary Systems overview
- Kepler's haul
- Individual Systems:
  - KOI-730, Kepler-11, -18, and -16

Radial Velocity Multiple Planets

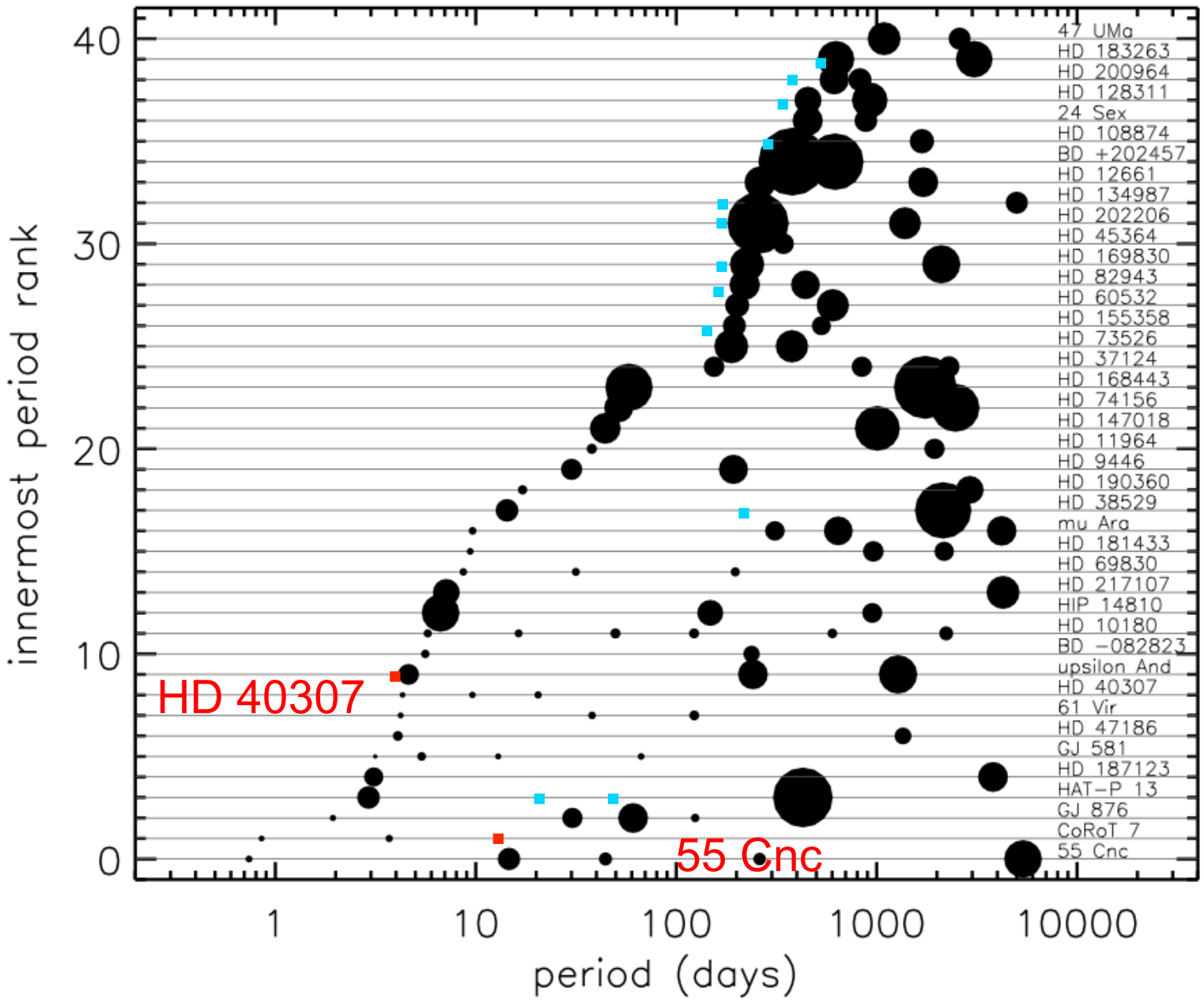


Low-mass planets: a different population?



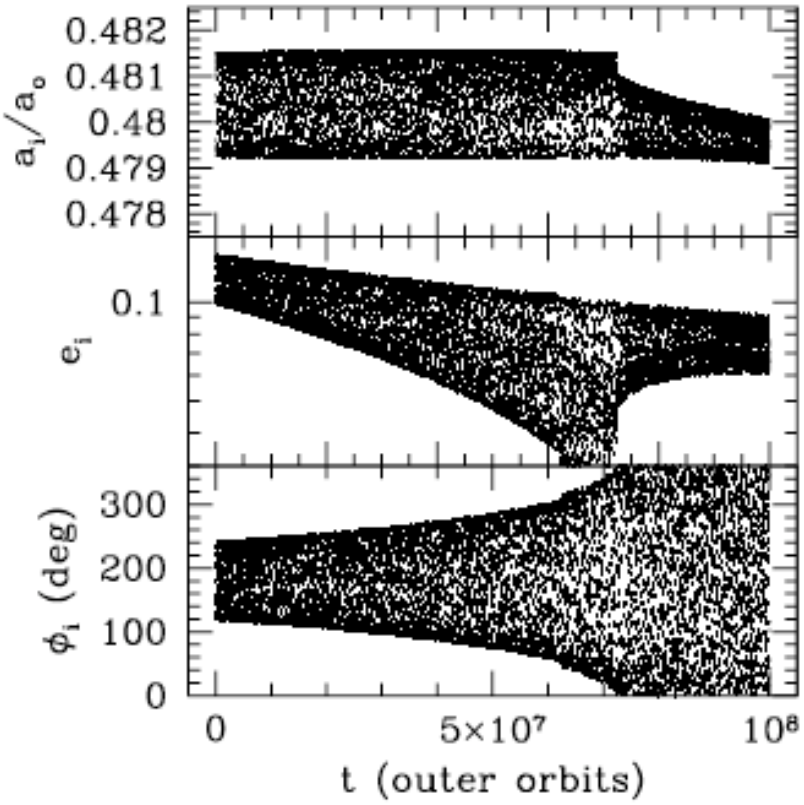


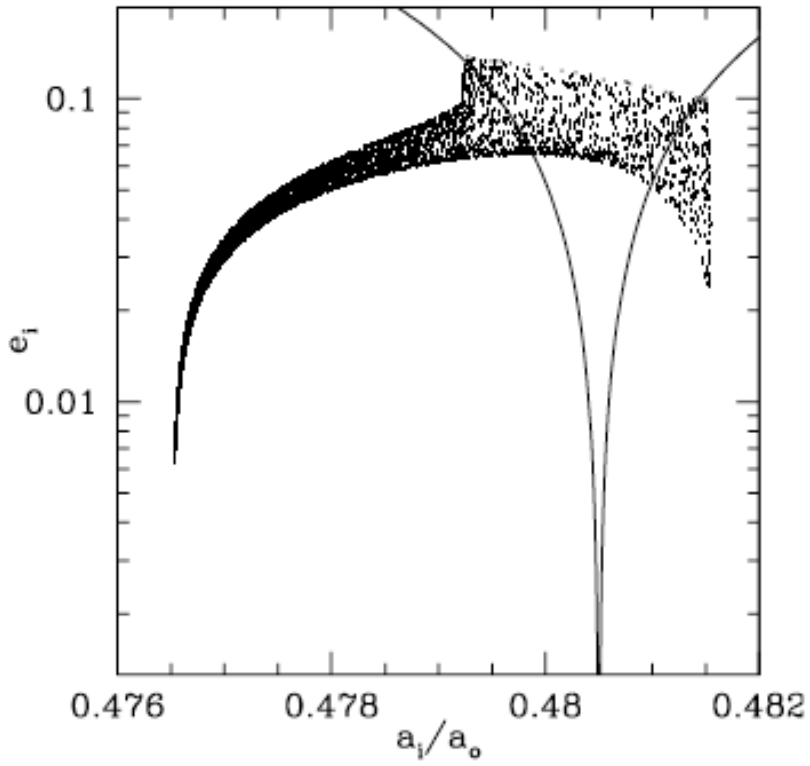
Resonances


innermost period rank
period (days)
0
10
20
30
40
1
10
100
1000
10000
HD 40307
55 Cnc
47 UMa
HD 183263
HD 200964
HD 128311
24 Sex
HD 108874
BD +202457
HD 12661
HD 134987
HD 202206
HD 45364
HD 169830
HD 82943
HD 60532
HD 155358
HD 73526
HD 37124
HD 168443
HD 74156
HD 147018
HD 11964
HD 9446
HD 190360
HD 38529
mu Ara
HD 181433
HD 69830
HD 217107
HIP 14810
HD 10180
BD −082823
upsilon And
HD 40307
61 Vir
HD 47186
GJ 581
HD 187123
HAT−P 13
GJ 876
CoRoT 7
55 Cnc

55 Cnc b-c

Name	Msin(i) mjupiter ±	Orbital Period days ±	Orbital Eccentricity ±
55 Cnc c	0.168	44.379	0.05
55 Cnc b	0.83	14.6513	0.016





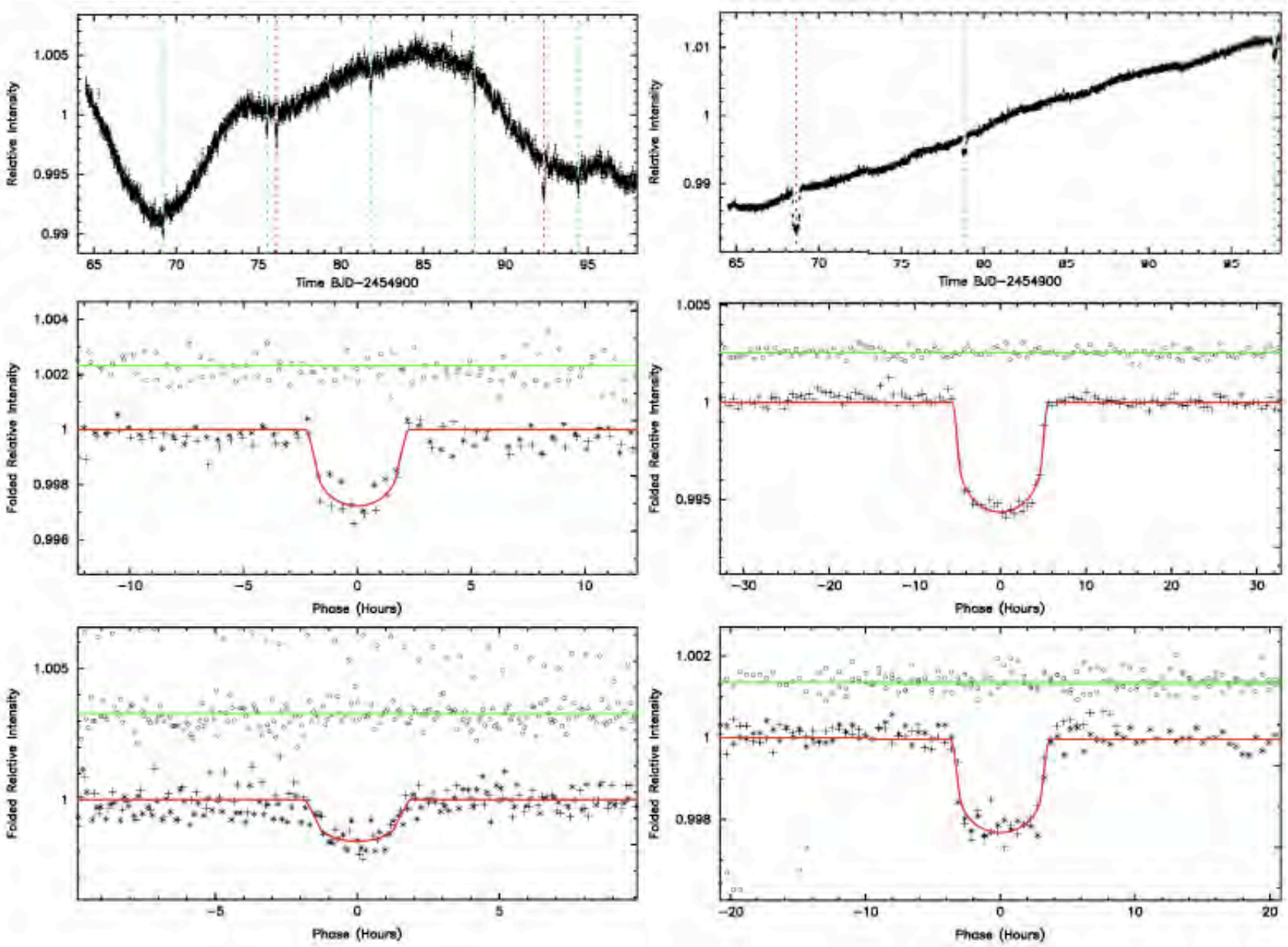
Novak, Lai, Lin 2003

see also: Terquem & Papaloizou 2008

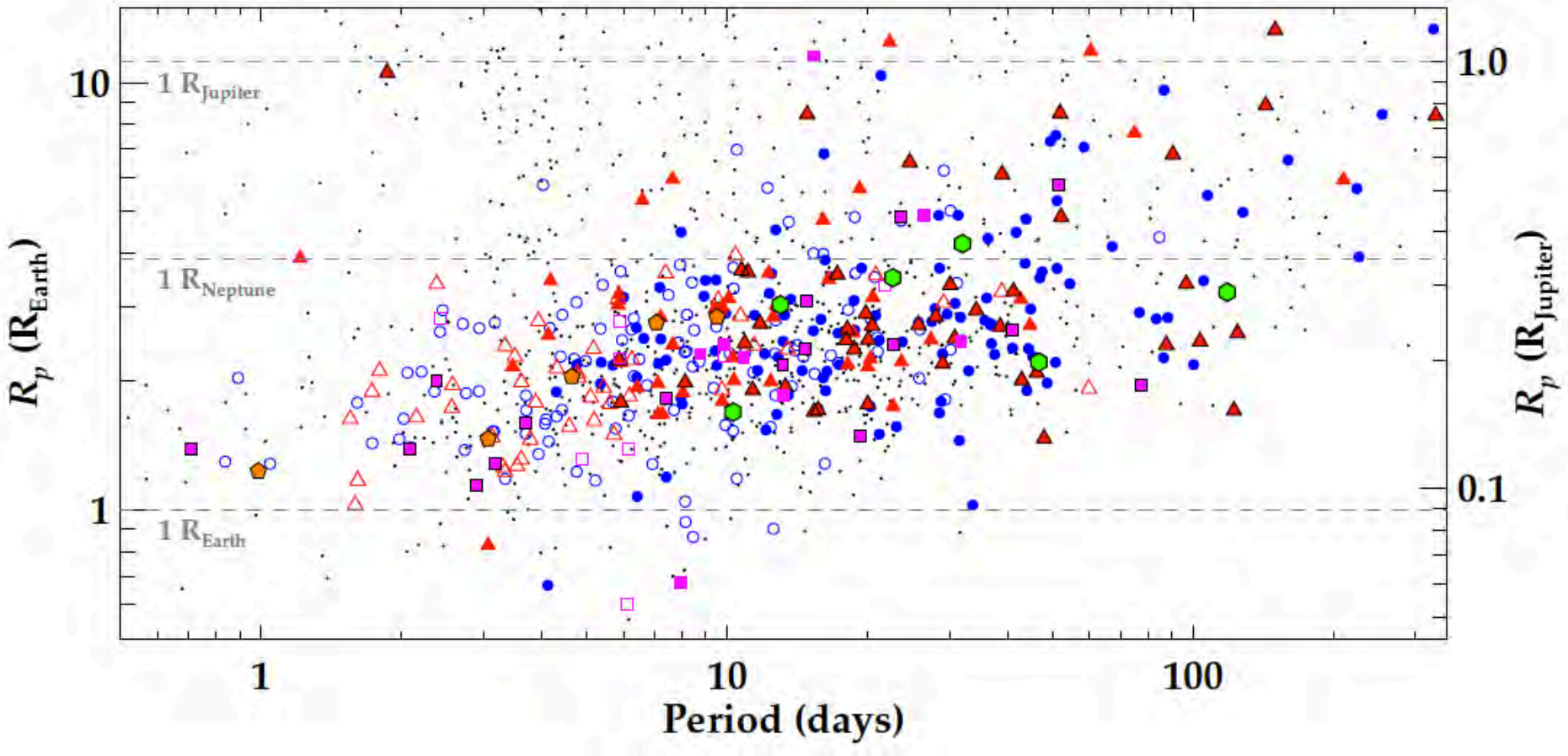
Kepler Mission

- NASA, photometry of 150,000 stars
- Looking for Earth-like planets in transit
- ~40 ppm in 6 hours; 30 minute cadence
- 210 days are public!

Kepler finds Multiplanets



(Steffen et al. 2010) Transit search and figures by Jason Rowe



Numbers of multiplanets:

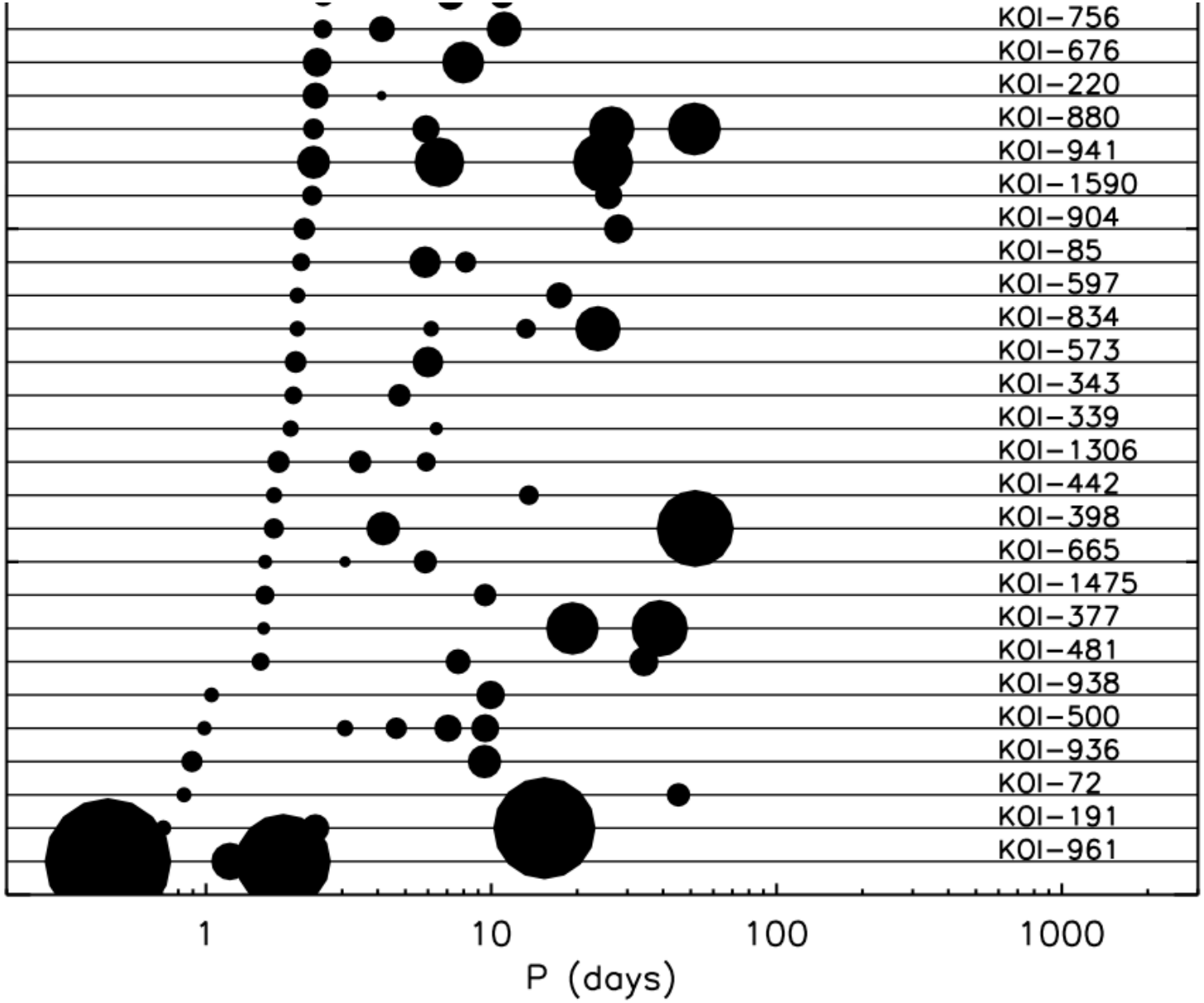
115 doubles, 45 triples, 8 quaduples,

1 quintuple and 1 sextuple

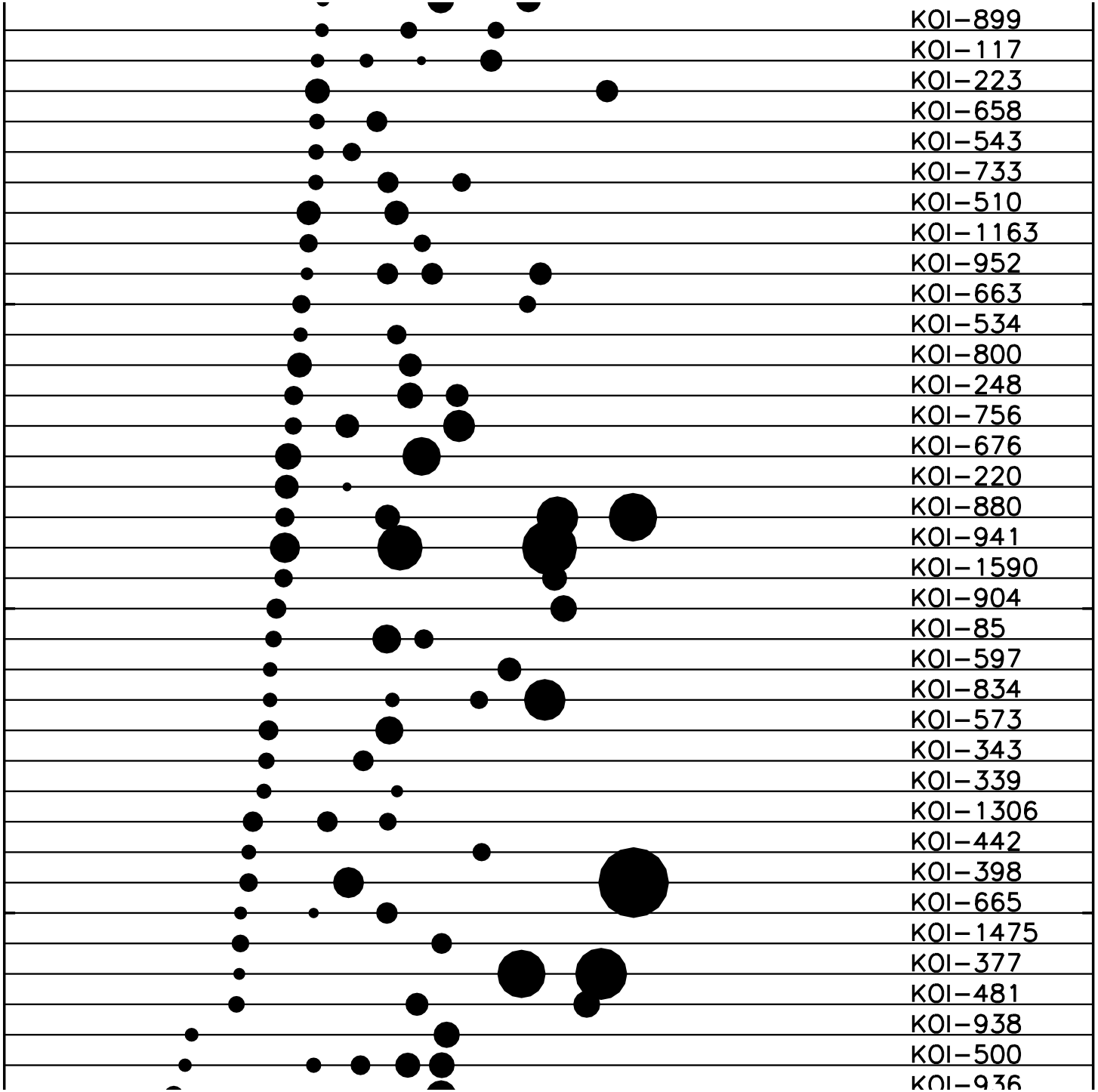
Borucki et al. 2011

Latham, Rowe, Quinn et al. 2011

Lissauer, Ragozzine, Fabrycky et al. 2011



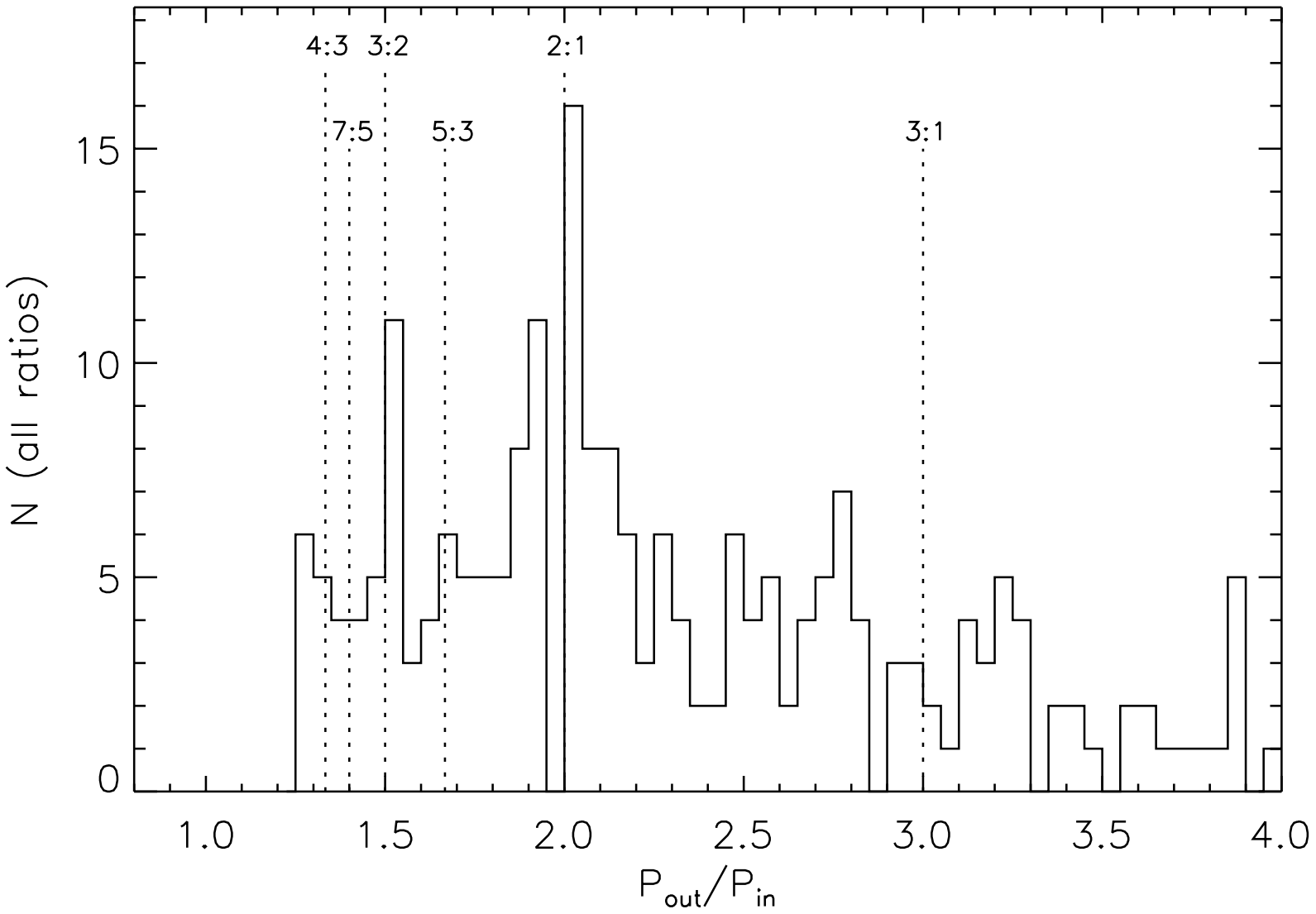
Kepler systems


KOI-899
KOI-117
KOI-223
KOI-658
KOI-543
KOI-733
KOI-510
KOI-1163
KOI-952
KOI-663
KOI-534
KOI-800
KOI-248
KOI-756
KOI-676
KOI-220
KOI-880
KOI-941
KOI-1590
KOI-904
KOI-85
KOI-597
KOI-834
KOI-573
KOI-343
KOI-339
KOI-1306
KOI-442
KOI-398
KOI-665
KOI-1475
KOI-377
KOI-481
KOI-938
KOI-500
KOI-936

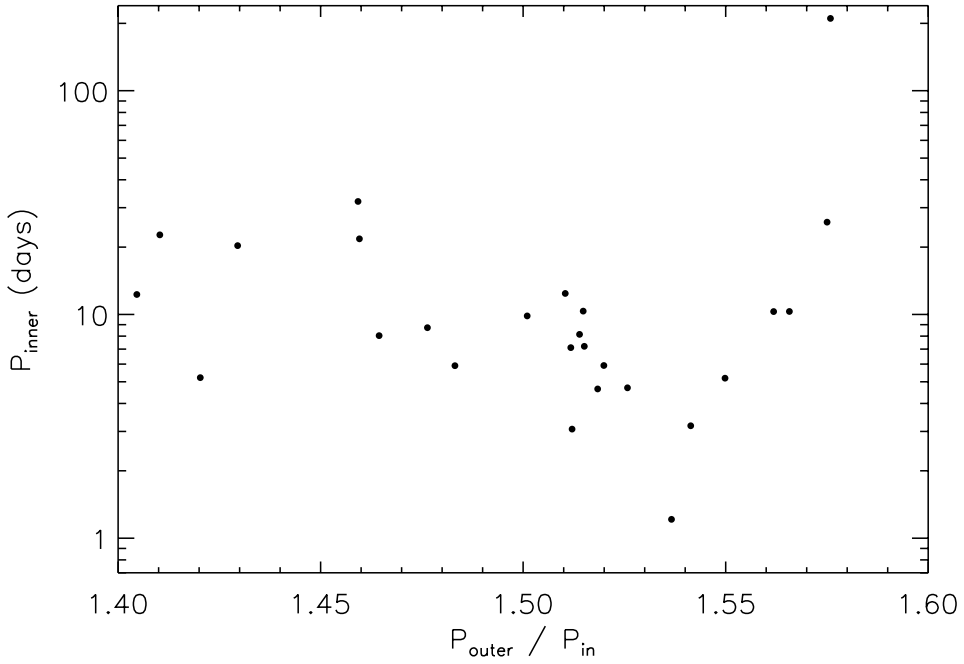
Kepler Orrery

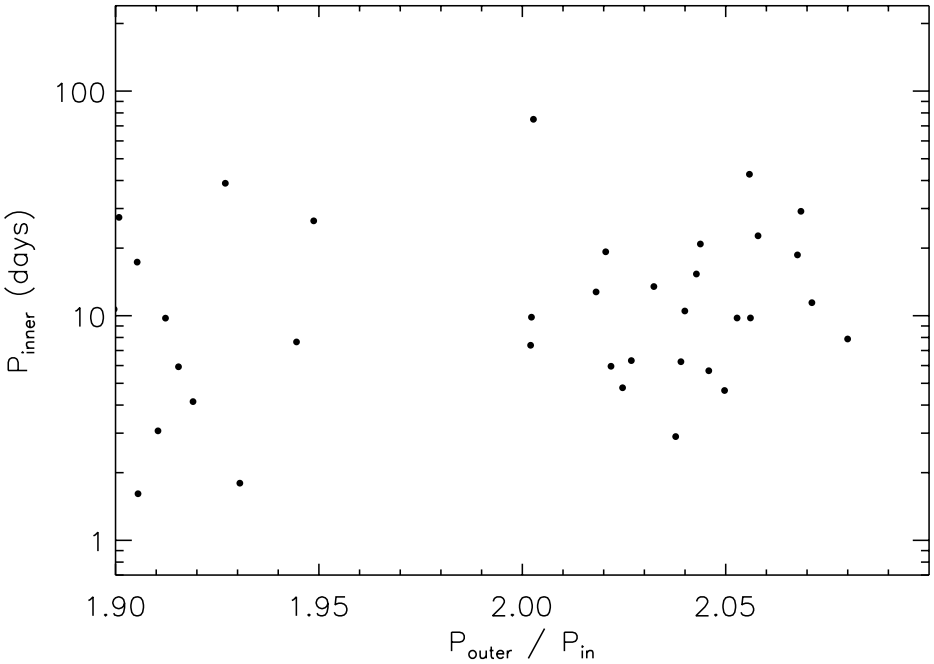
- http://www.youtube.com/watch?v=qRJ30fkyiU4

Resonance Preference

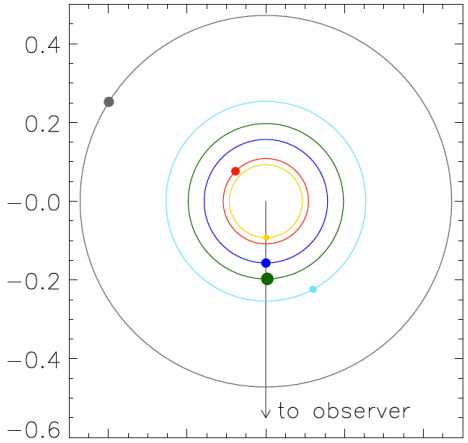


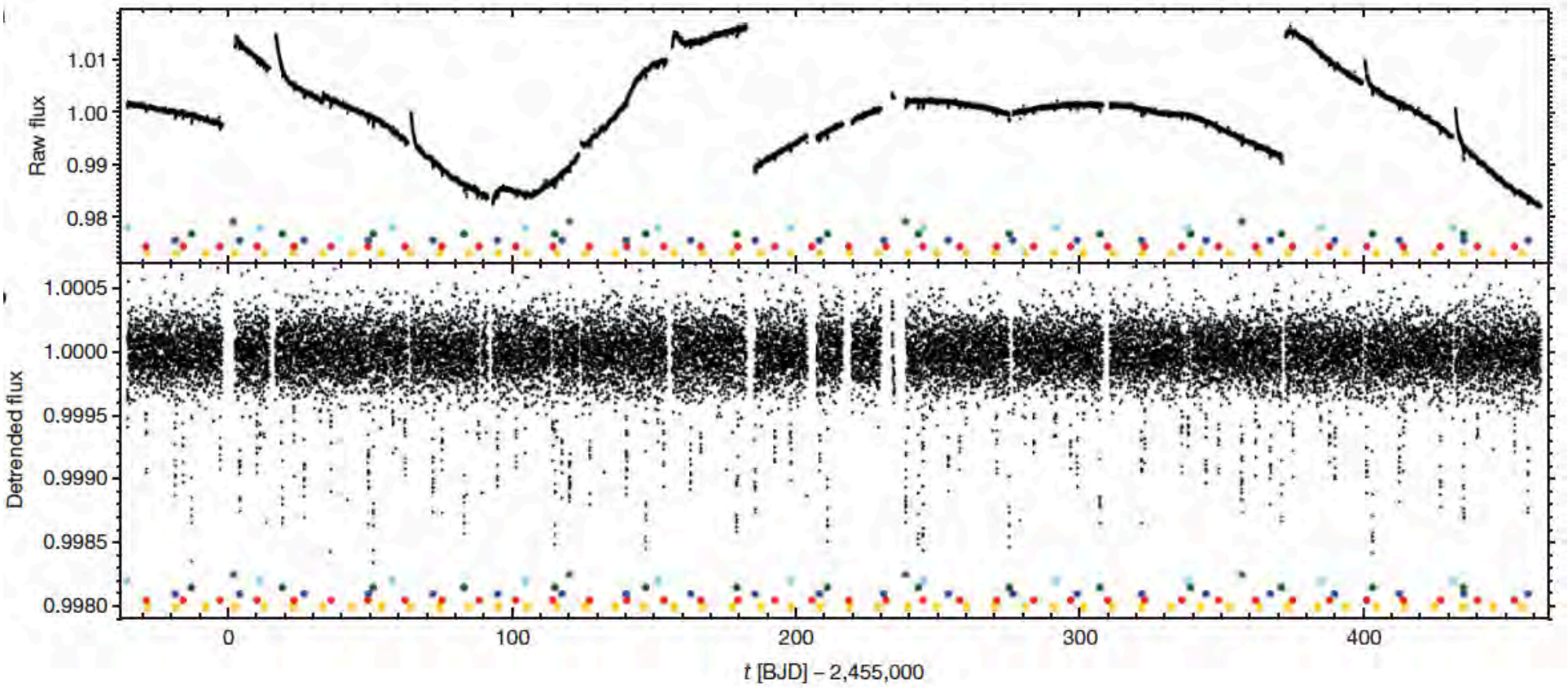
Resonance Preference



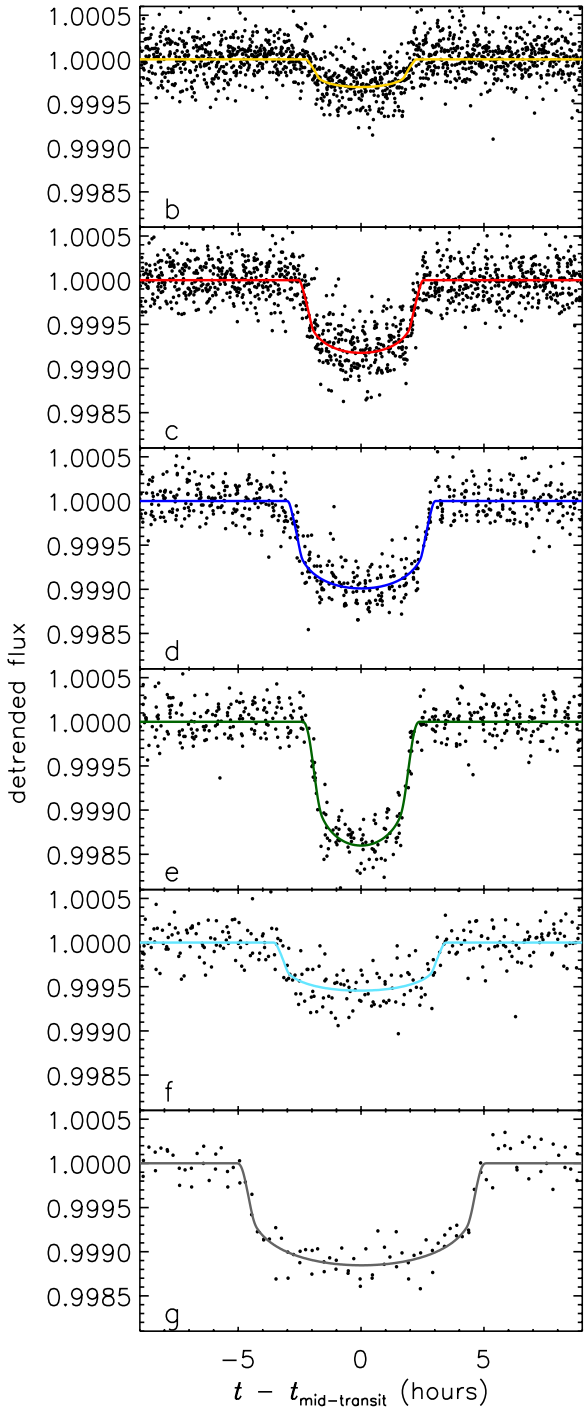


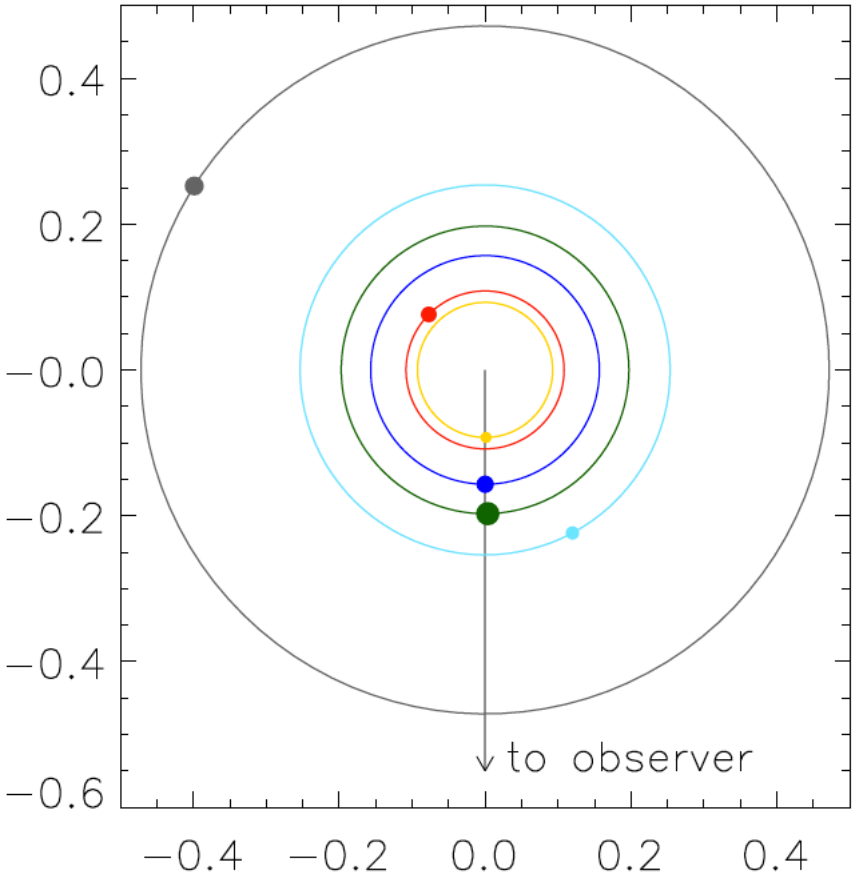
Kepler-11

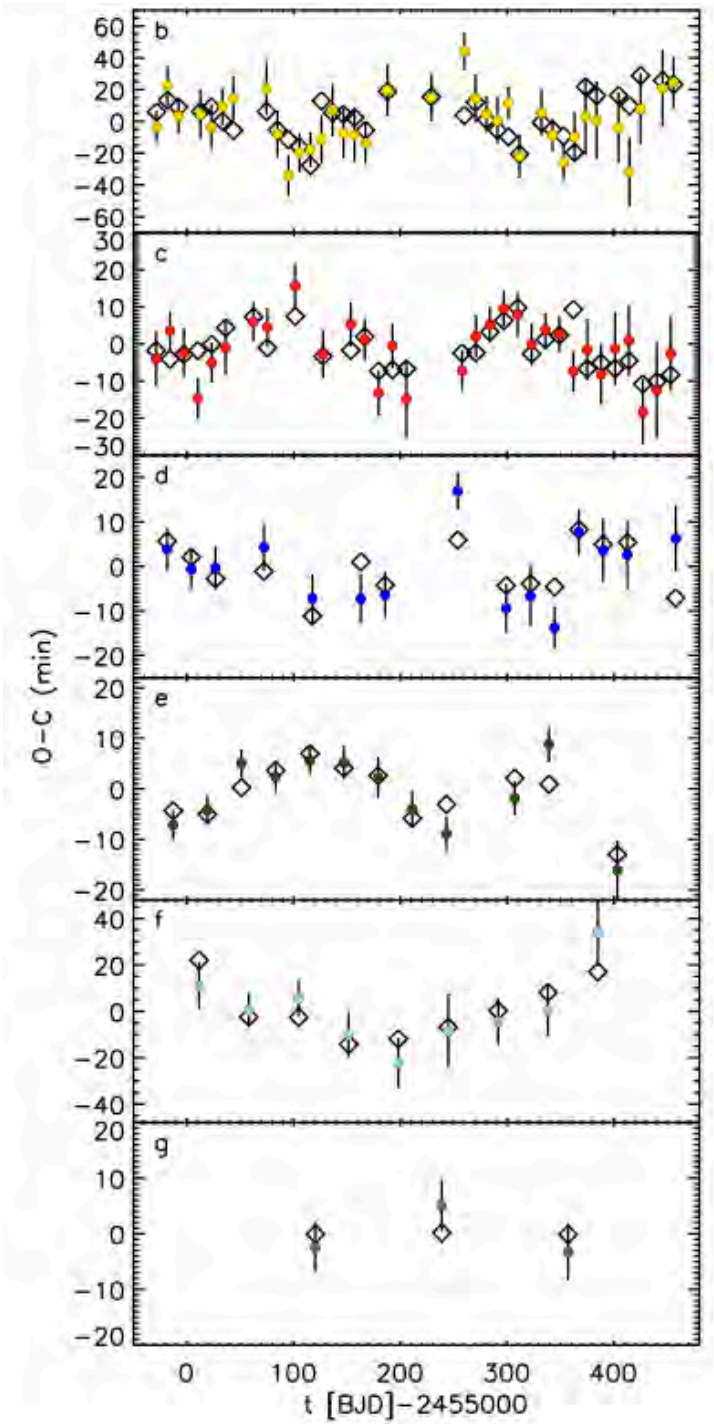


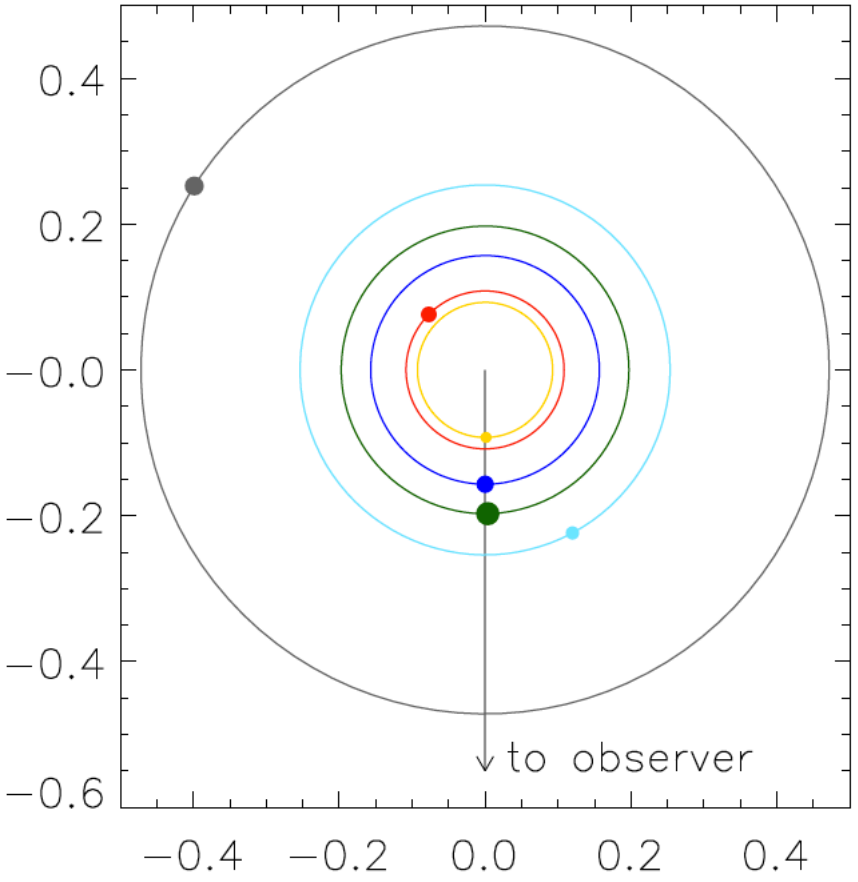


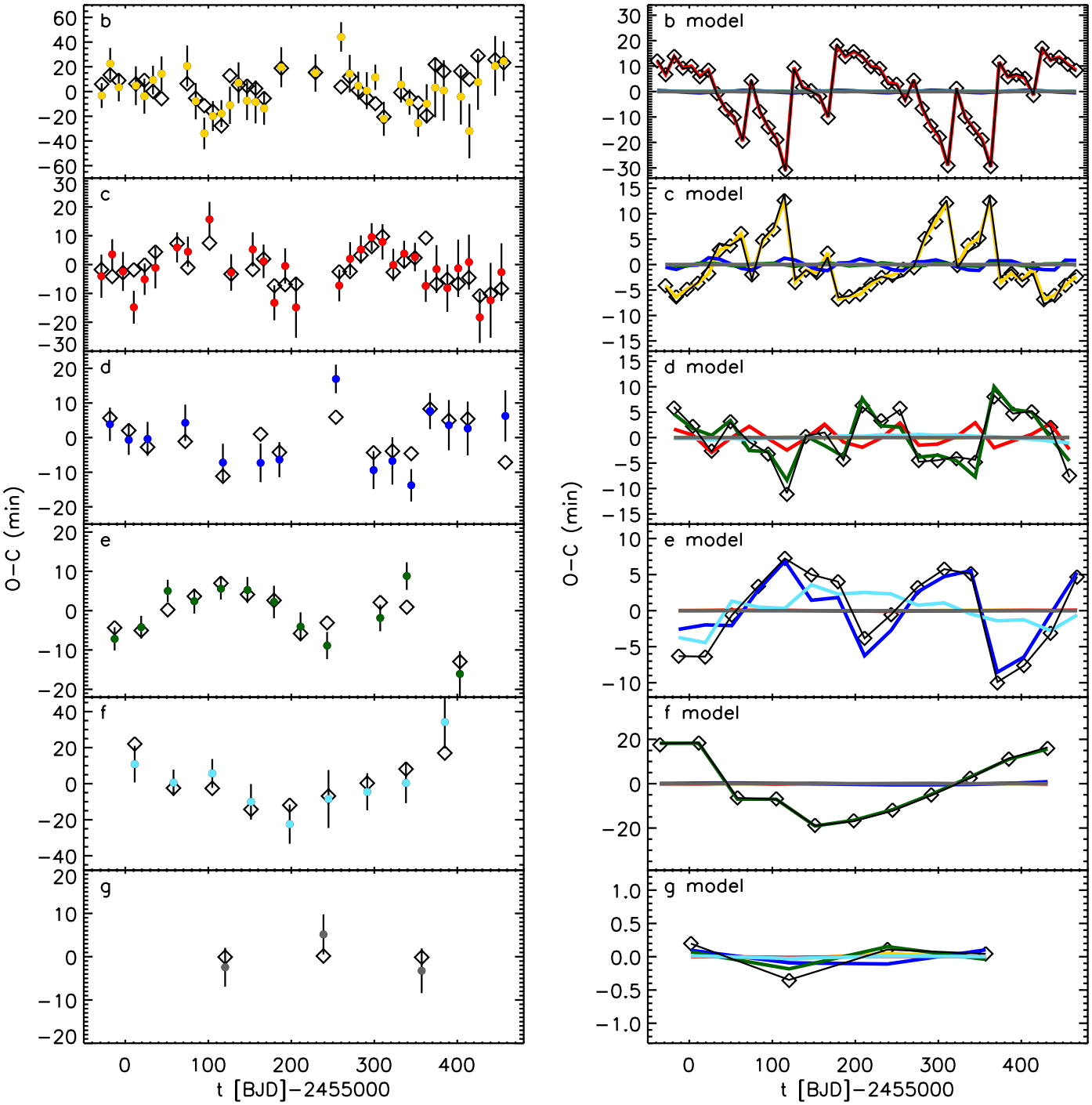
Lissauer, Fabrycky, Ford et al. 2011


1.0005
1.0000
0.9995
0.9990
0.9985
b
c
d
e
f
g
detrended flux
−5
0
5
t − t_mid−transit (hours)


0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer

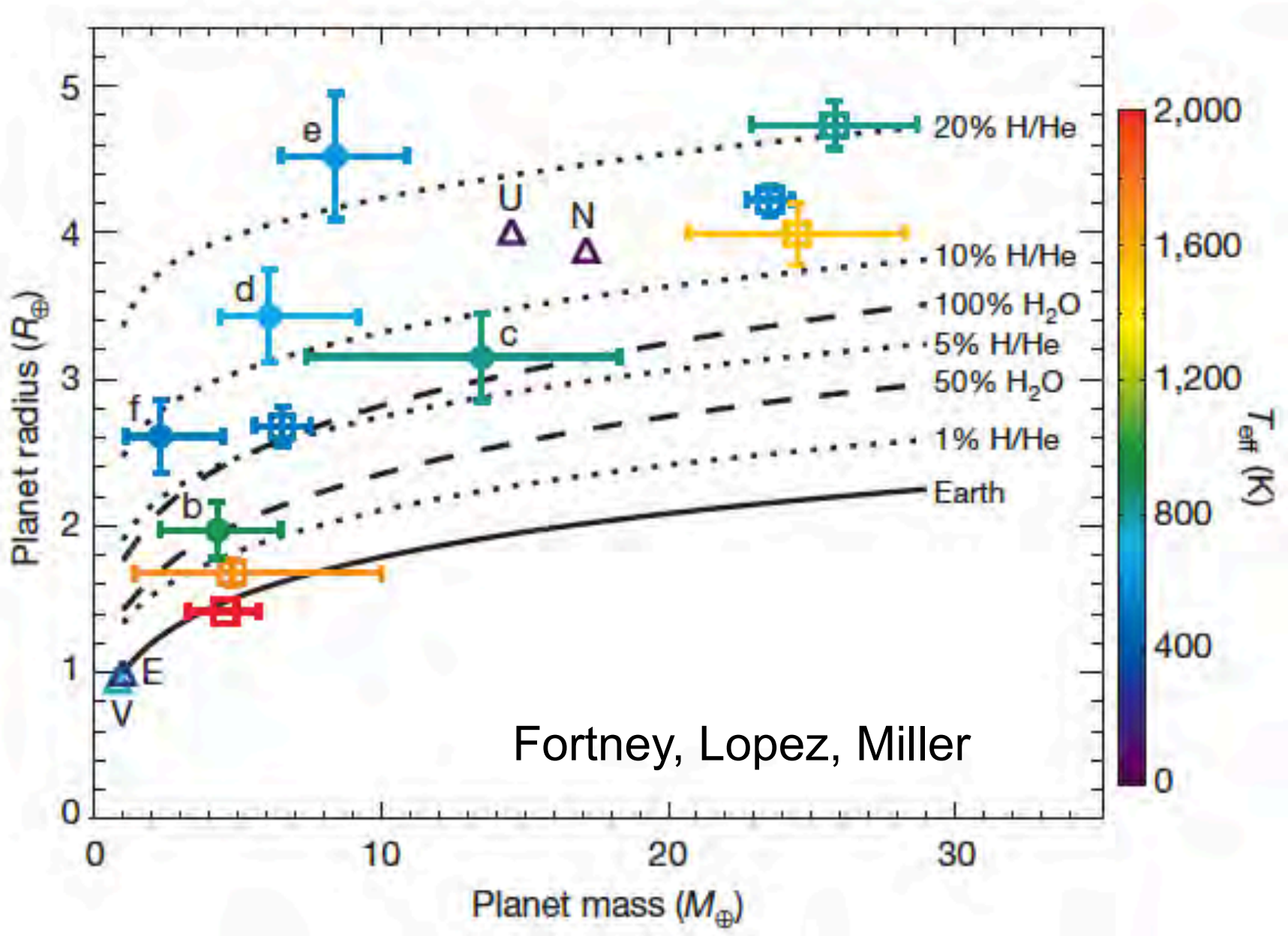

b
c
d
e
f
g
O−C (min)
t [BJD]−2455000
0
100
200
300
400


0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer


b
c
d
e
f
g
O−C (min)
t [BJD]−2455000
b model
c model
d model
e model
f model
g model
O−C (min)
t [BJD]−2455000

Kepler-11 parameters

Planet	Period (days)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g/cm³)
	10.30375	**1.97**	**4.3**	**3.1**
b	± 0.00016	± 0.19	+2.2,-2.0	+2.1,-1.5
	13.02502	**3.15**	**13.5**	**2.3**
c	± 0.00008	± 0.30	+4.8,-6.1	+1.3,-1.1
	22.68719	**3.43**	**6.1**	**0.9**
d	± 0.00021	± 0.32	+3.1,-1.7	+0.5,-0.3
	31.99590	**4.52**	**8.4**	**0.5**
e	± 0.00028	± 0.43	+2.5,-1.9	+0.2,-0.2
	46.68876	**2.61**	**2.3**	**0.7**
f	± 0.00074	± 0.25	+2.2,-1.2	+0.7,-0.4
	118.37774	**3.66**		-
g	± 0.00112	± 0.35	< 300	


Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
T_{eff} (K)
2,000
1,600
1,200
800
400
0
20% H/He
10% H/He
100% H_2O
5% H/He
50% H_2O
1% H/He
Earth
e
d
c
f
b
U
N
E
V
Fortney, Lopez, Miller

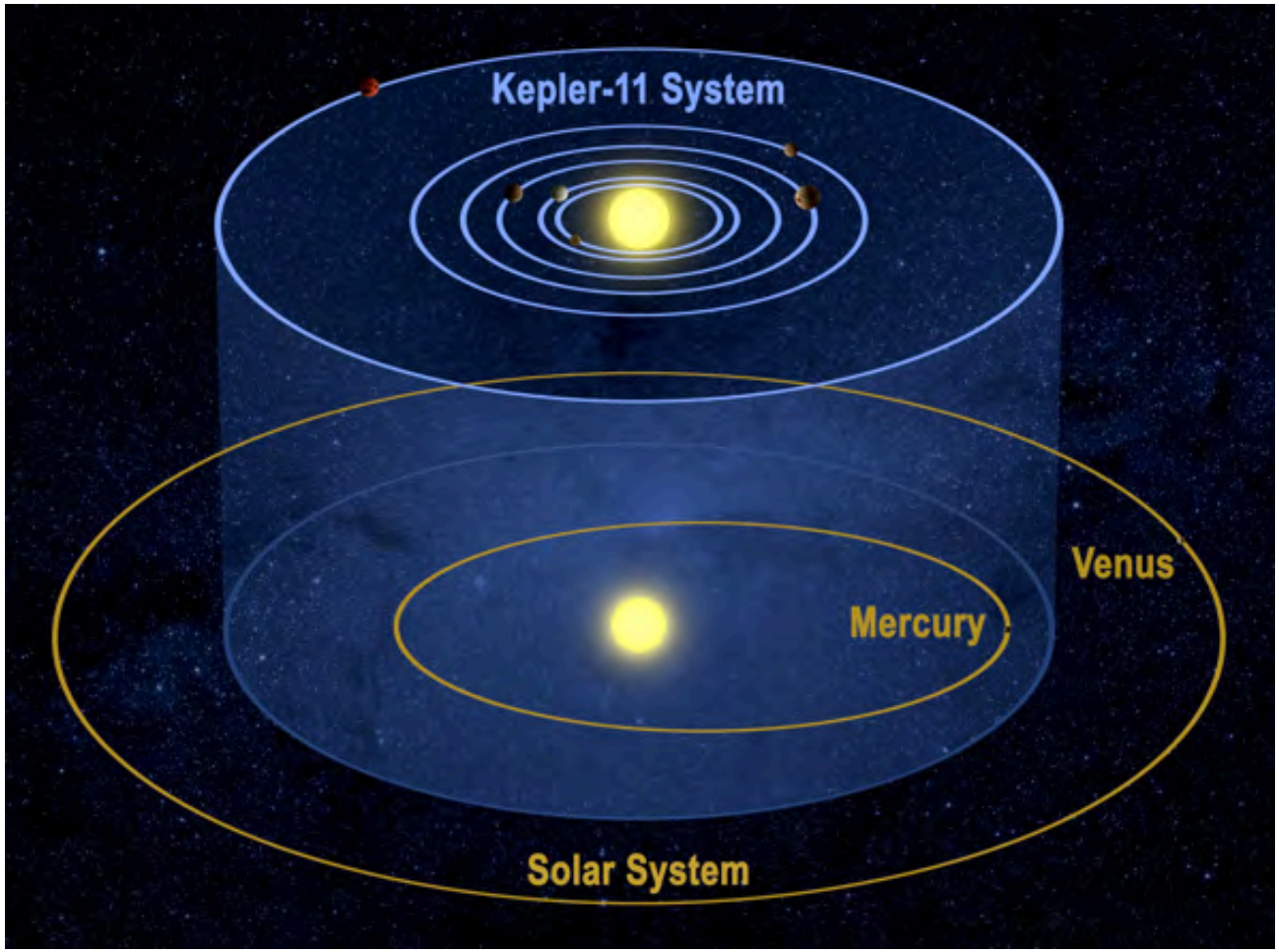


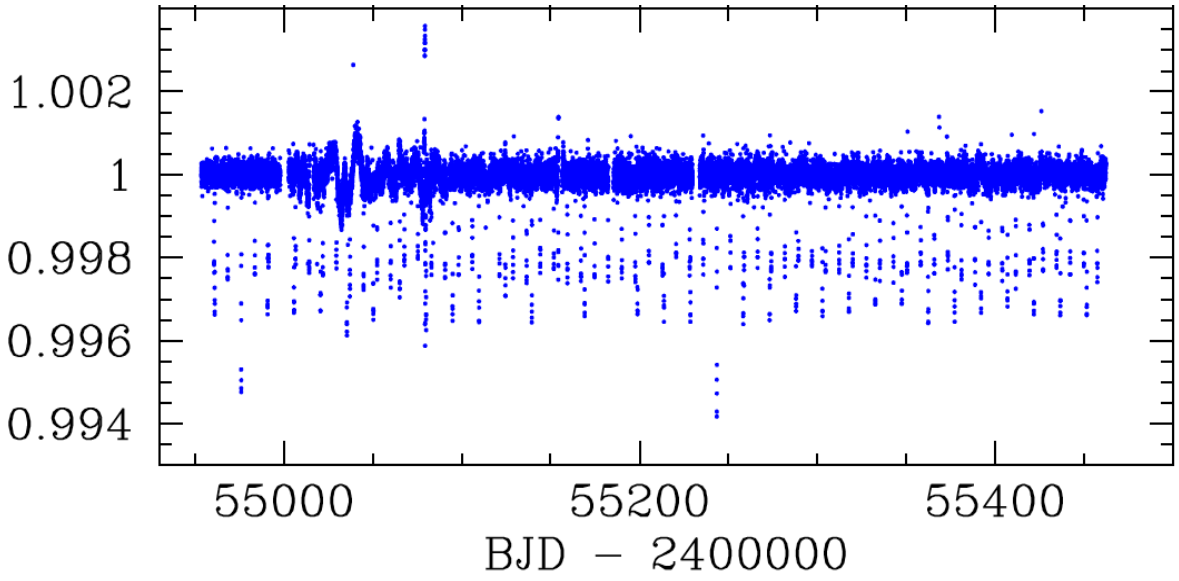
Image: NASA/Pyle

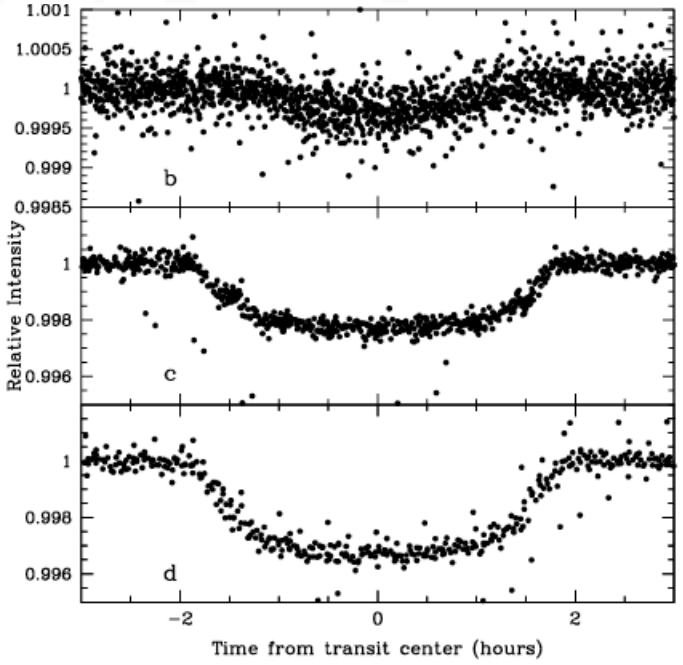
Kepler-18

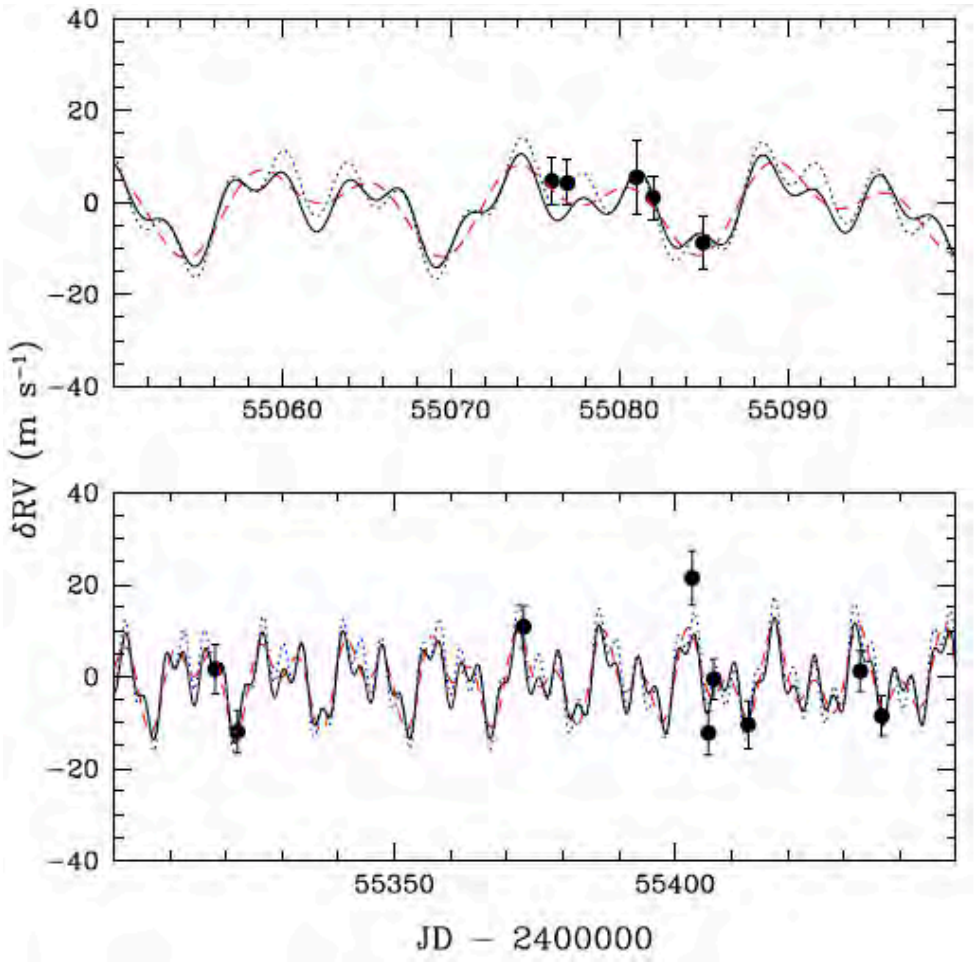
Kepler-18b, c, and d: A SYSTEM OF THREE PLANETS CONFIRMED BY TRANSIT TIMING VARIATIONS, LIGHTCURVE VALIDATION, *Warm-Spitzer* PHOTOMETRY AND RADIAL VELOCITY MEASUREMENTS

William D. Cochran[1], Daniel C. Fabrycky[2], Guillermo Torres[3], François Fressin[3], Jean-Michel Désert[3], Darin Ragozzine[3], Dimitar Sasselov[3], Jonathan J. Fortney[2], Jason F. Rowe[4], Erik J. Brugamyer[5], Stephen T. Bryson[4], Joshua A. Carter[3], David R. Ciardi[6], Steve B. Howell[4], Jason H. Steffen[7], William. J. Borucki[4], David G. Koch[4], Joshua N. Winn [8], William F. Welsh[9], Kamal Uddin[10,4], Peter Tenenbaum[15,4], M. Still[11,4], Sara Seager[8], Samuel N. Quinn[3], F. Mullally[15,4], Neil Miller[2], Geoffrey W. Marcy[12], Phillip J. MacQueen[1], Philip Lucas[13], Jack J. Lissauer[4], David W. Latham[3], Heather Knutson[12], K. Kinemuchi[11,4], John A. Johnson[14], Jon M. Jenkins[15,4], Howard Isaacson[12], Andrew Howard[12], Elliott Horch[16], Matthew J. Holman[3], Christopher E. Henze[4], Michael R. Haas[4], Ronald L. Gilliland[17], Thomas N. Gautier III[18], Eric B. Ford[19], Debra A. Fischer[20], Mark Everett[21], Michael Endl[1], Brice-Oliver Demory[8], Drake Deming[22], David Charbonneau[3], Douglas Caldwell[15,4], Lars Buchhave[23,24], Timothy M. Brown[25], and Natalie Batalha[26]

ApJS in press

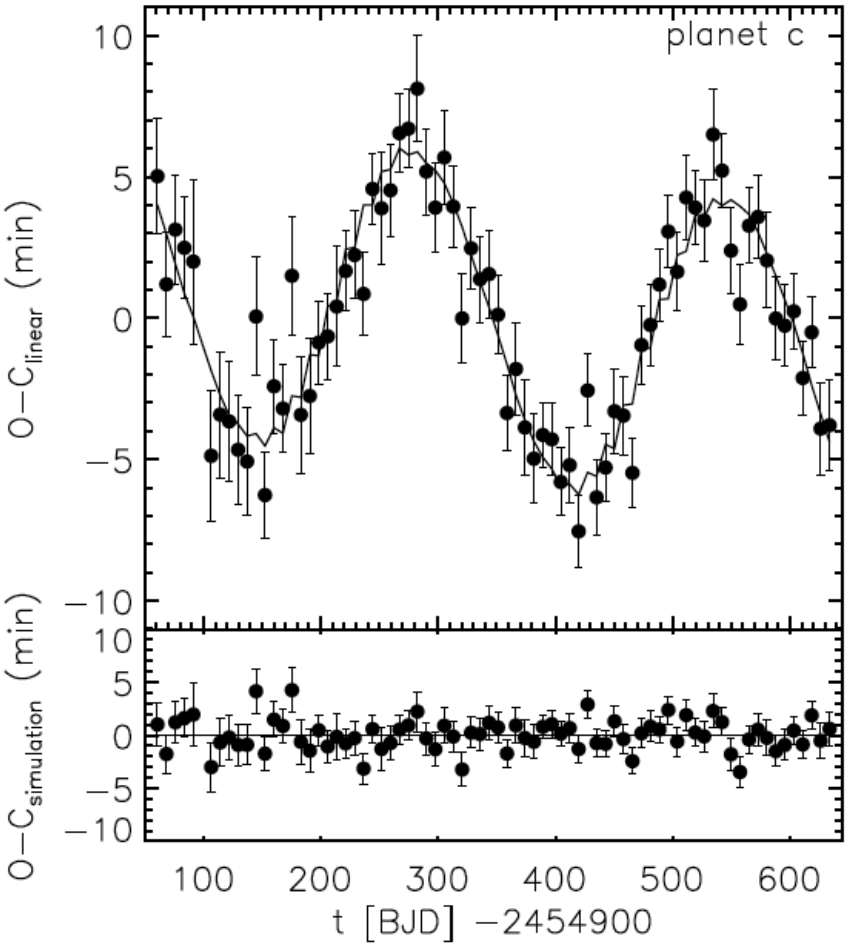




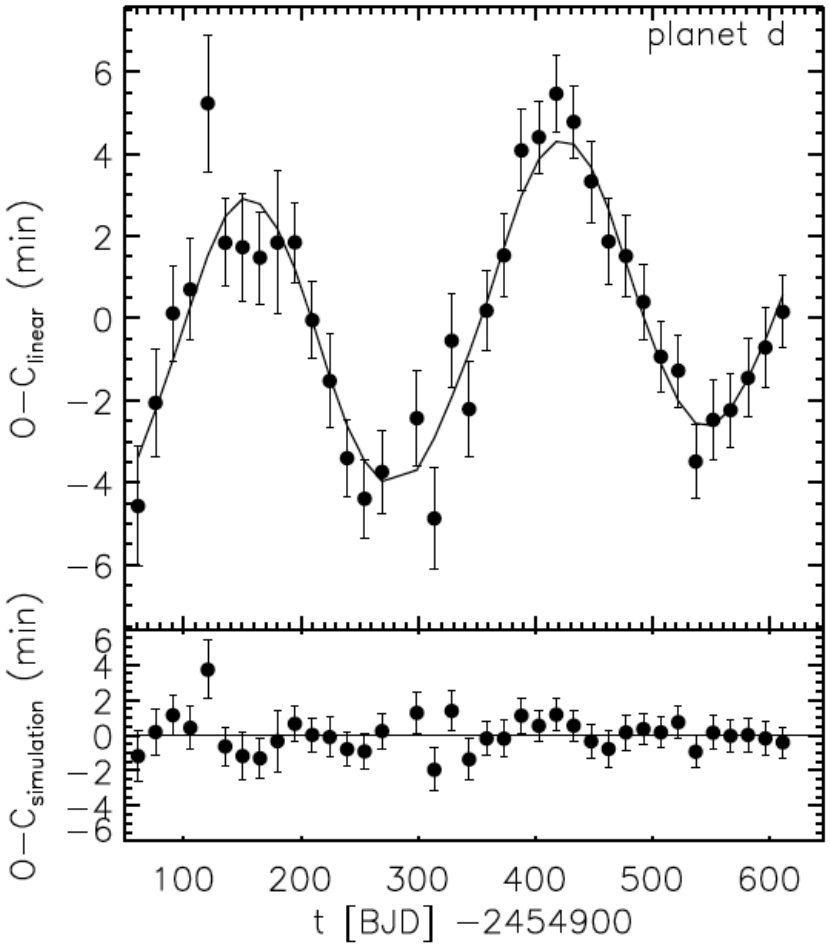


Planet	Period (days)	Mass (M_{Earth})
b	3.5	12 ± 5
c	7.6	15 ± 5
d	14.9	28 ± 7

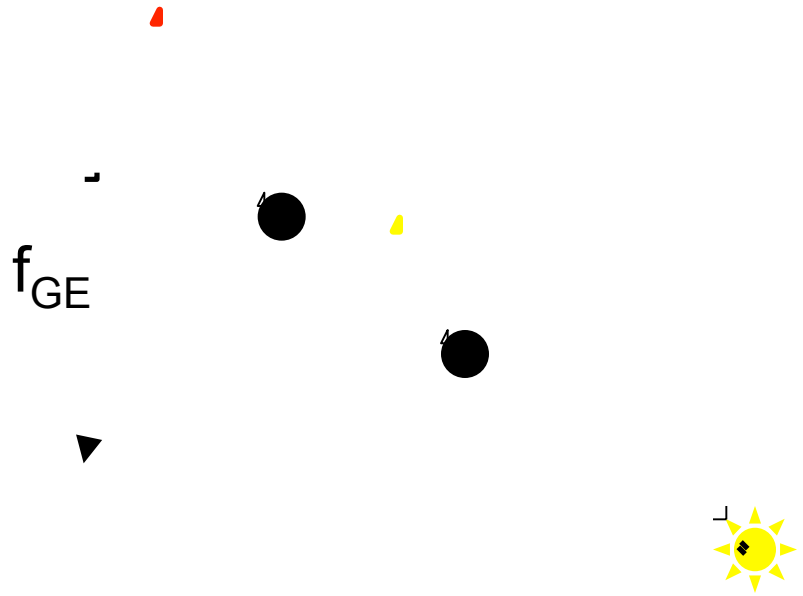
P = 7.6416 days



P = 14.8589 days



P/P=1.944 ~= 2/1

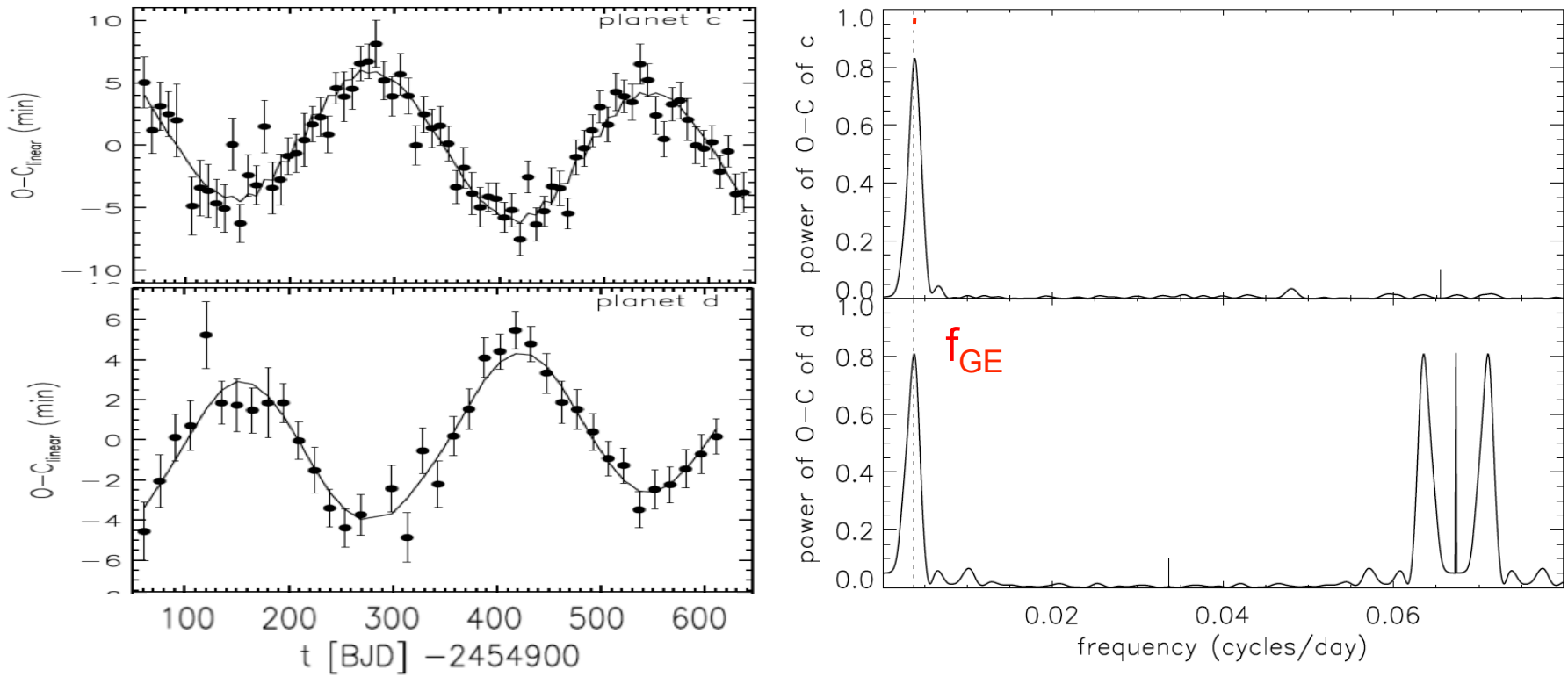


"Great Inequality" frequency:

$f_{GE}=2/P-1/P$

$= 0.0037\ d^{-1}$

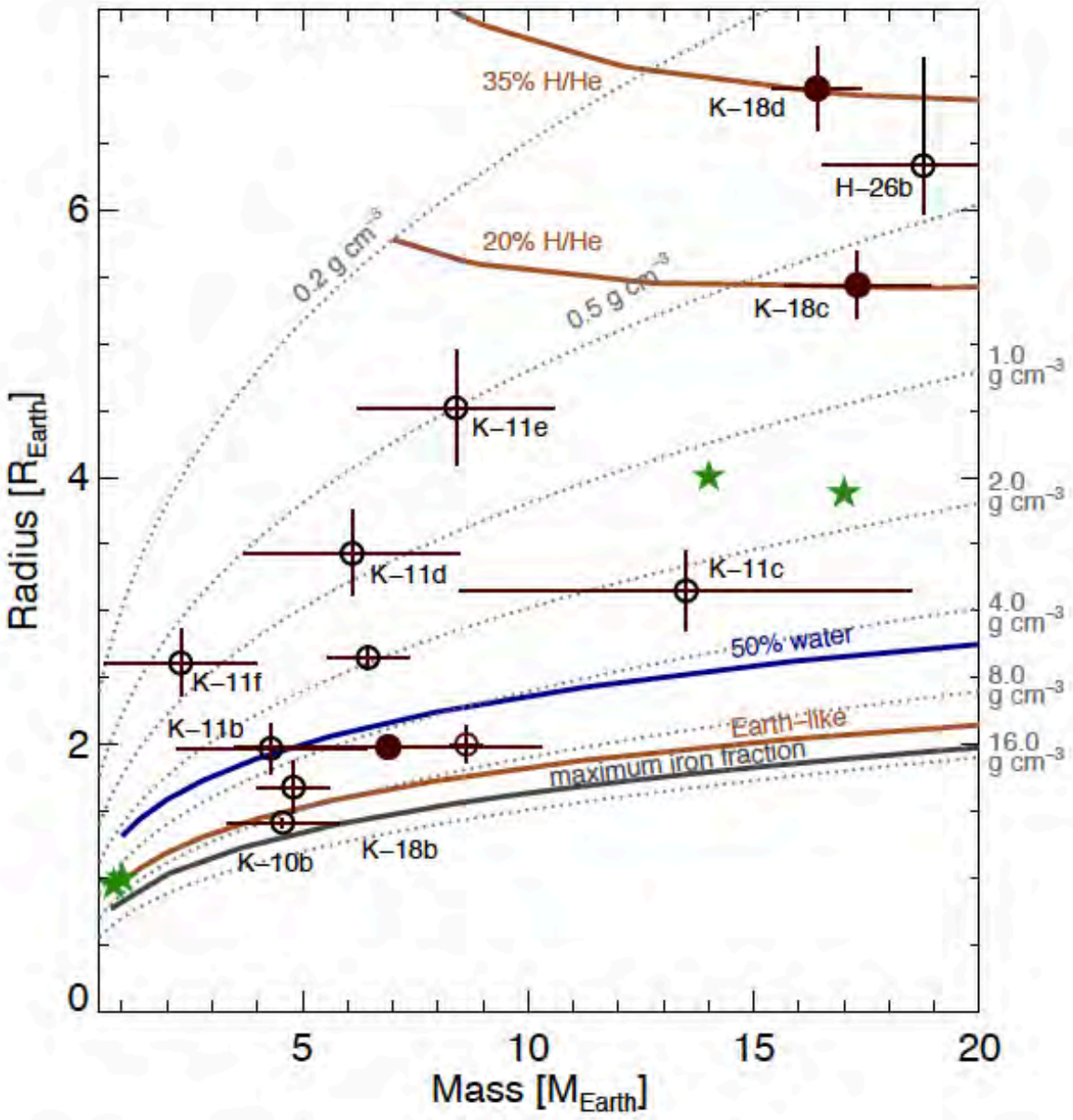
or 270 days



The Great Inequality is observed!

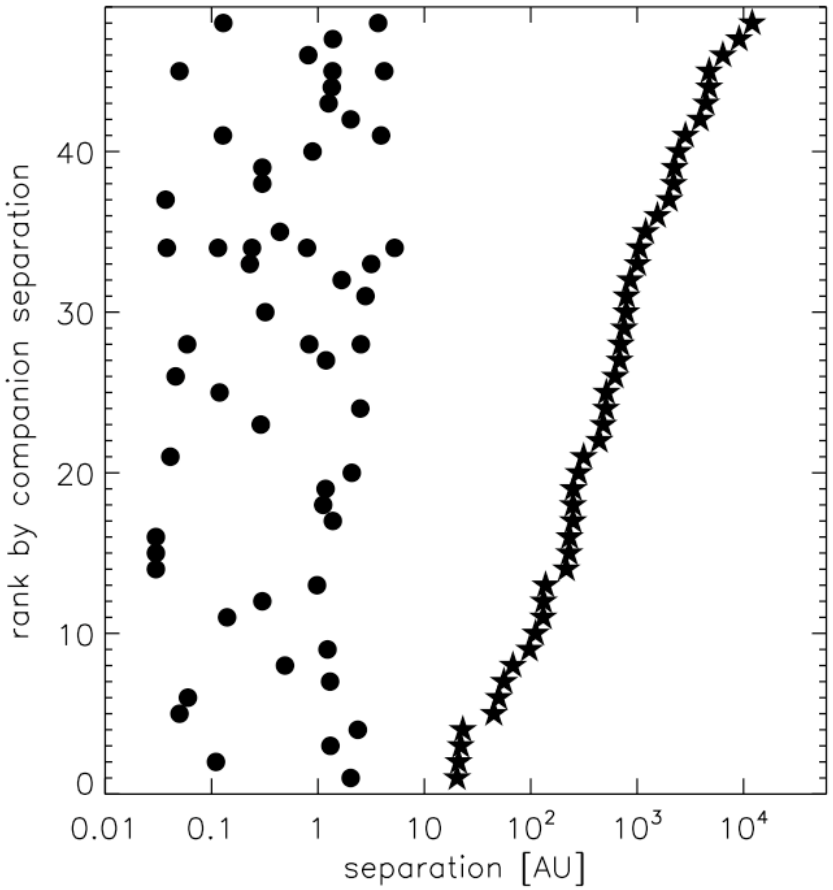
Kepler-18 tests TTV masses

Planet	Period (days)	RV Mass (M_{Earth})	TTV Mass (M_{Earth})
b	3.5	12 ± 5	18 ± 9
c	7.6	15 ± 5	17.3 ± 1.7
d	14.9	28 ± 7	15.8 ± 1.3


35% H/He
20% H/He
0.2 g cm^{-3}
0.5 g cm^{-3}
K–18d
H–26b
K–18c
K–11e
K–11d
K–11c
K–11f
K–11b
K–10b
K–18b
50% water
Earth–like
maximum iron fraction
1.0 g cm^{-3}
2.0 g cm^{-3}
4.0 g cm^{-3}
8.0 g cm^{-3}
16.0 g cm^{-3}
Radius [R_{Earth}]
Mass [M_{Earth}]
0
2
4
6
5
10
15
20

Planets in Binaries

~50 systems known,
via Doppler plus
imaging follow-up

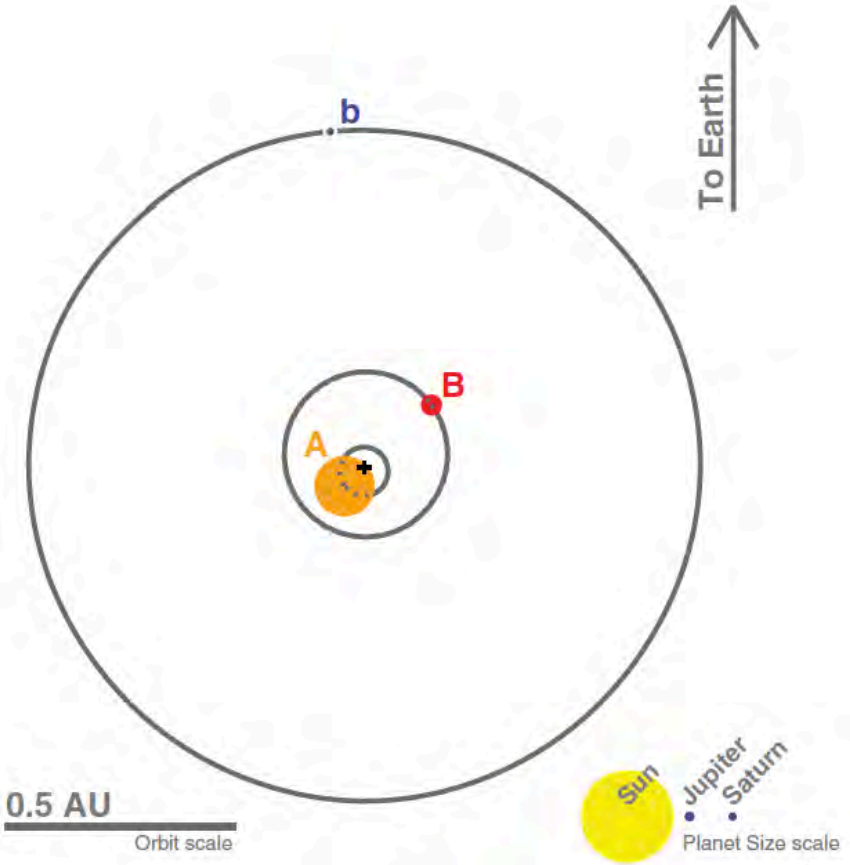


But can we find
planets orbiting
both stars?

Kepler-16(AB)b

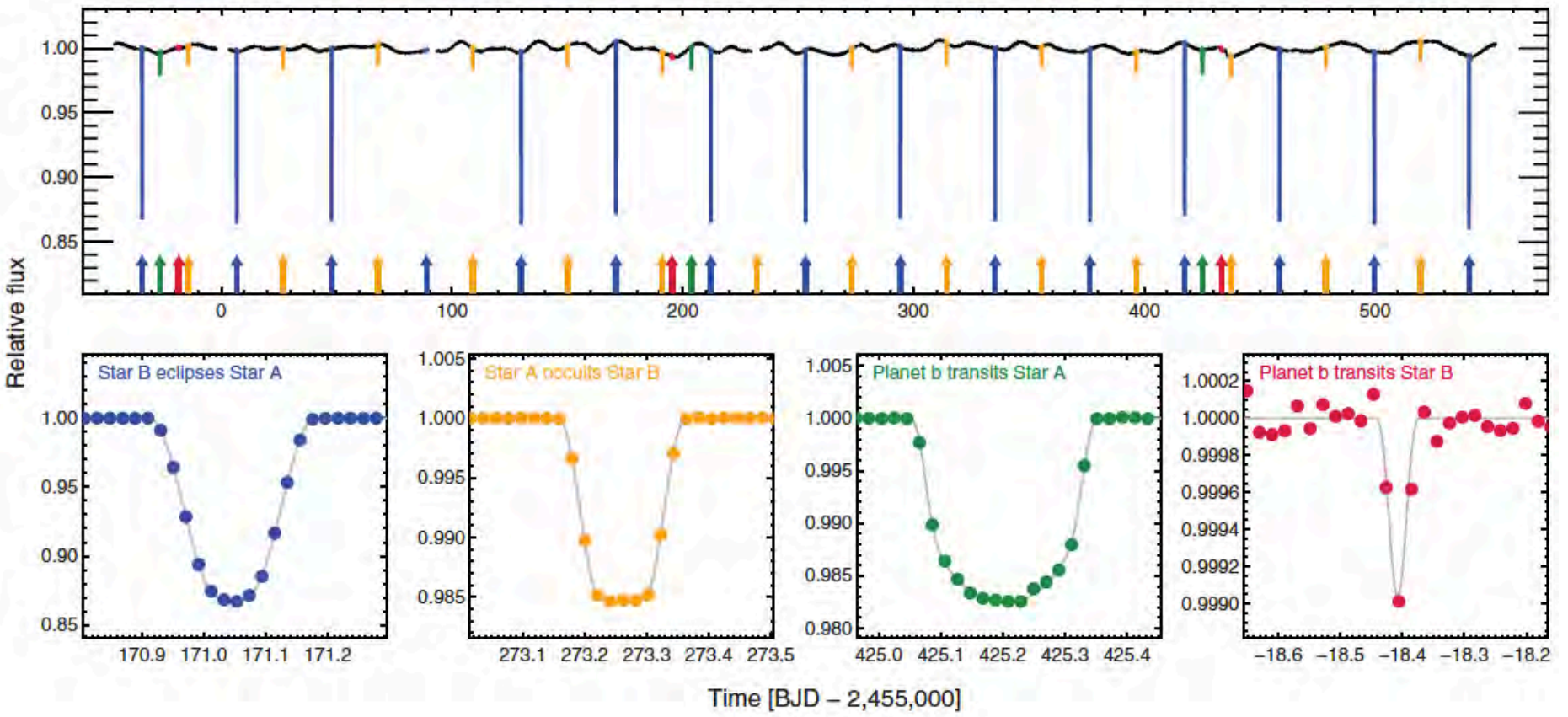
- http://www.youtube.com/watch?v=0MfRo0eC1ks
- http://www.youtube.com/watch?v=AaE0KK7m3VA

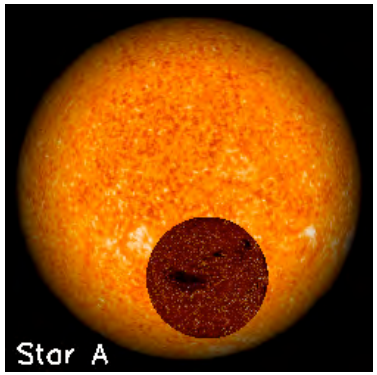
credit: Tim Pyle (NASA)

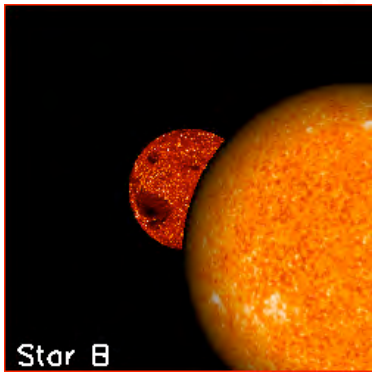


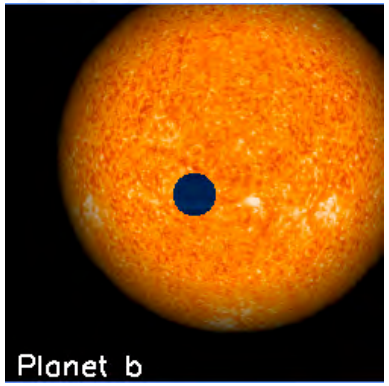
Kepler-16: A Transiting Circumbinary Planet

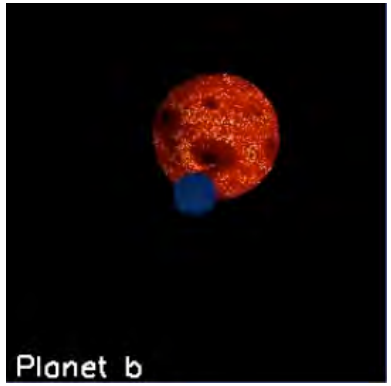
Laurance R. Doyle,[1*] Joshua A. Carter,[2] Daniel C. Fabrycky,[3] Robert W. Slawson,[1] Steve B. Howell,[4] Joshua N. Winn,[5] Jerome A. Orosz,[6] Andrej Prˇsa,[7] William F. Welsh,[6] Samuel N. Quinn,[8] David Latham,[8] Guillermo Torres,[8] Lars A. Buchhave,[9,19] Geoffrey W. Marcy,[11] Jonathan J. Fortney,[12] Avi Shporer,[13,14] Eric B. Ford,[15] Jack J. Lissauer,[4] Darin Ragozzine,[2] Michael Rucker,[16] Natalie Batalha,[16] Jon M. Jenkins,[1] William J. Borucki,[4] David Koch,[4] Christopher K. Middour,[17] Jennifer R. Hall,[17] Sean McCauliff,[17] Michael N. Fanelli,[18] Elisa V. Quintana,[1] Matthew J. Holman,[8] Douglas A. Caldwell,[1] Martin Still,[18] Robert P. Stefanik,[8] Warren R. Brown,[8] Gilbert A. Esquerdo,[8] Sumin Tang,[8] Gabor Furesz,[8,10] John C. Geary,[8] Perry Berlind,[20] Michael L. Calkins,[20] Donald R. Short,[21] Jason H. Steffen,[22] Dimitar Sasselov,[8] Edward W. Dunham,[23] William D. Cochran,[24] Alan Boss,[25] Michael R. Haas,[4] Derek Buzasi,[26] Debra Fischer[27]


Relative flux
1.00
0.95
0.90
0.85
0
100
200
300
400
500
Star B eclipses Star A
Star A occults Star B
Planet b transits Star A
Planet b transits Star B
1.005
1.000
0.995
0.990
0.985
0.980
1.0002
1.0000
0.9998
0.9996
0.9994
0.9992
0.9990
170.9
171.0
171.1
171.2
273.1
273.2
273.3
273.4
273.5
425.0
425.1
425.2
425.3
425.4
−18.6
−18.5
−18.4
−18.3
−18.2
Time [BJD – 2,455,000]

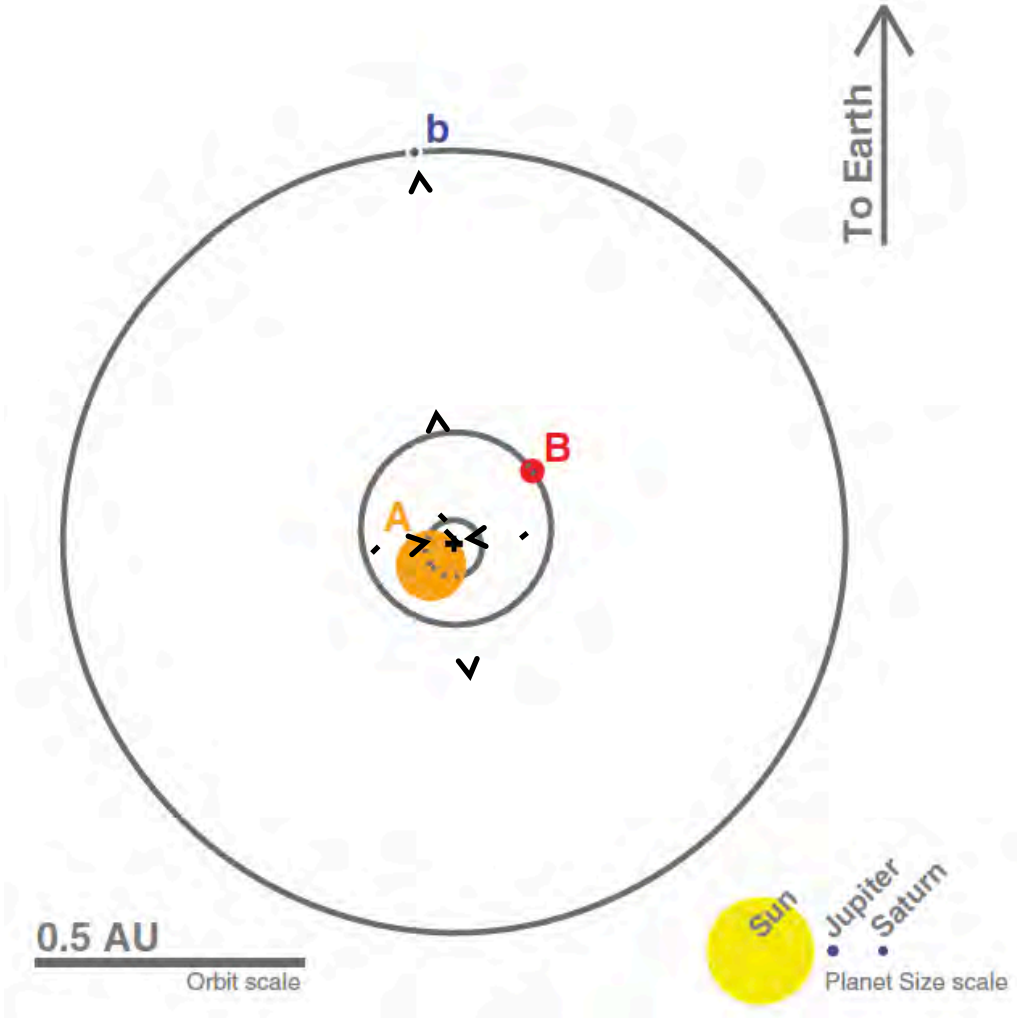

Star A


Star B

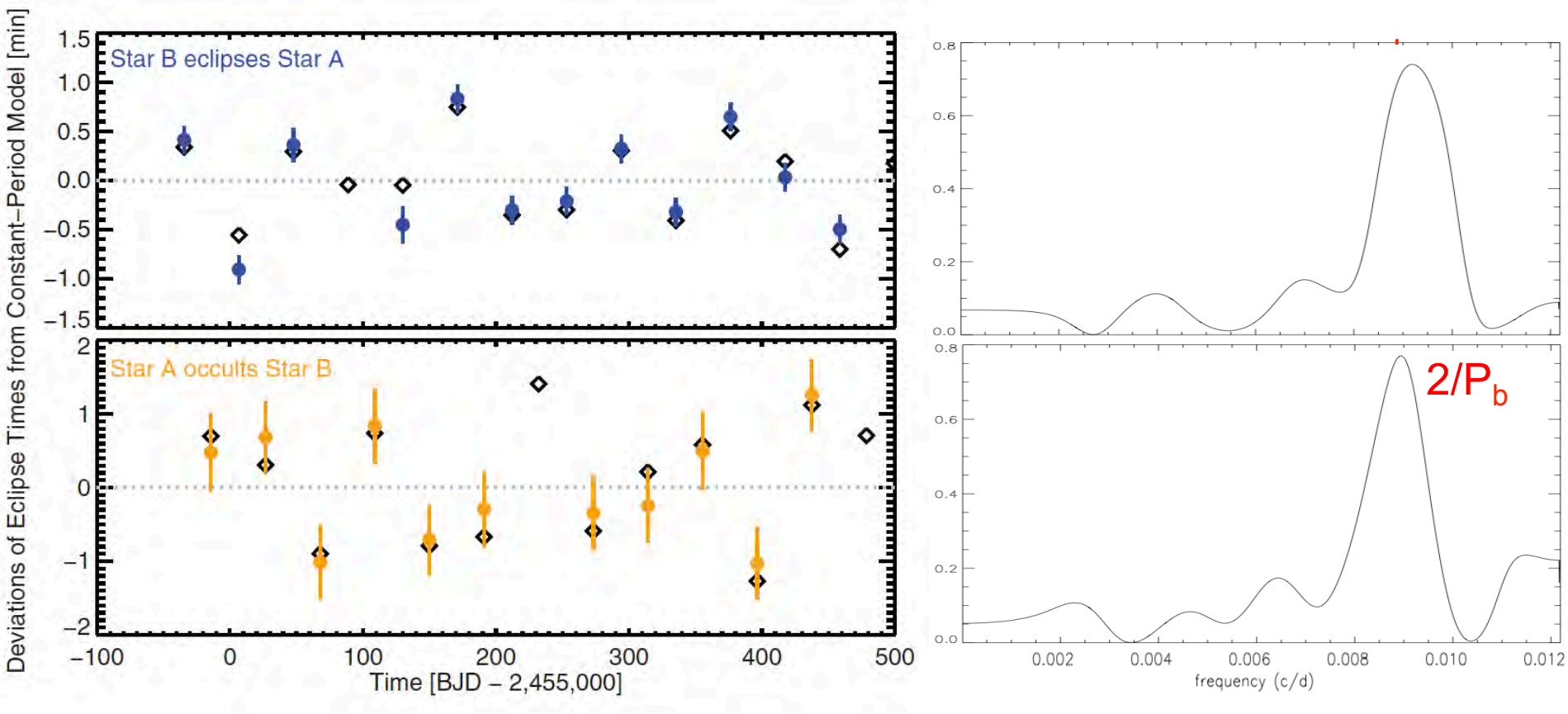

Planet b


Planet b

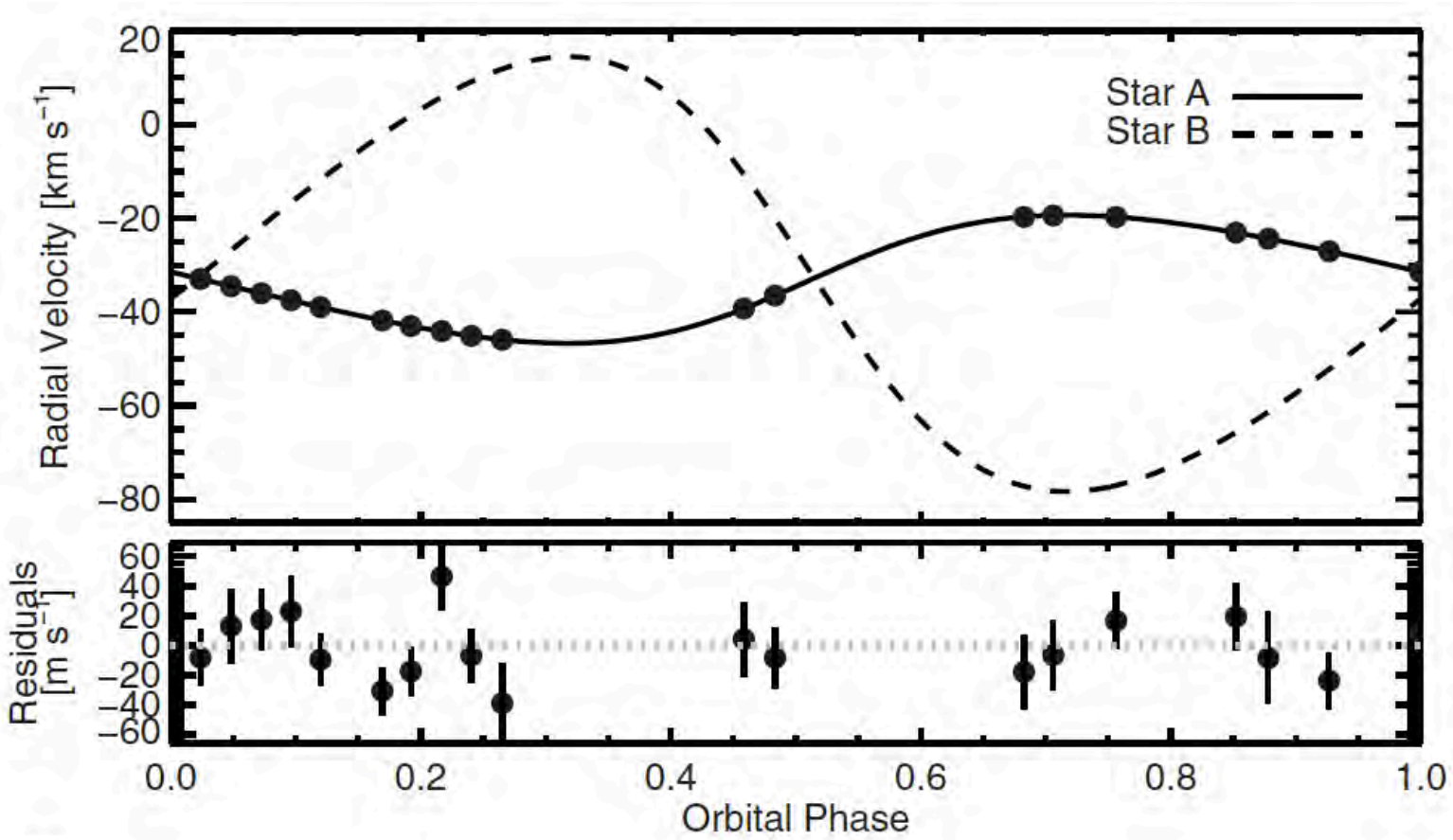
The mass of b?


b
To Earth
B
A
0.5 AU
Orbit scale
Sun
Jupiter
Saturn
Planet Size scale

Eclipse Timing Variations



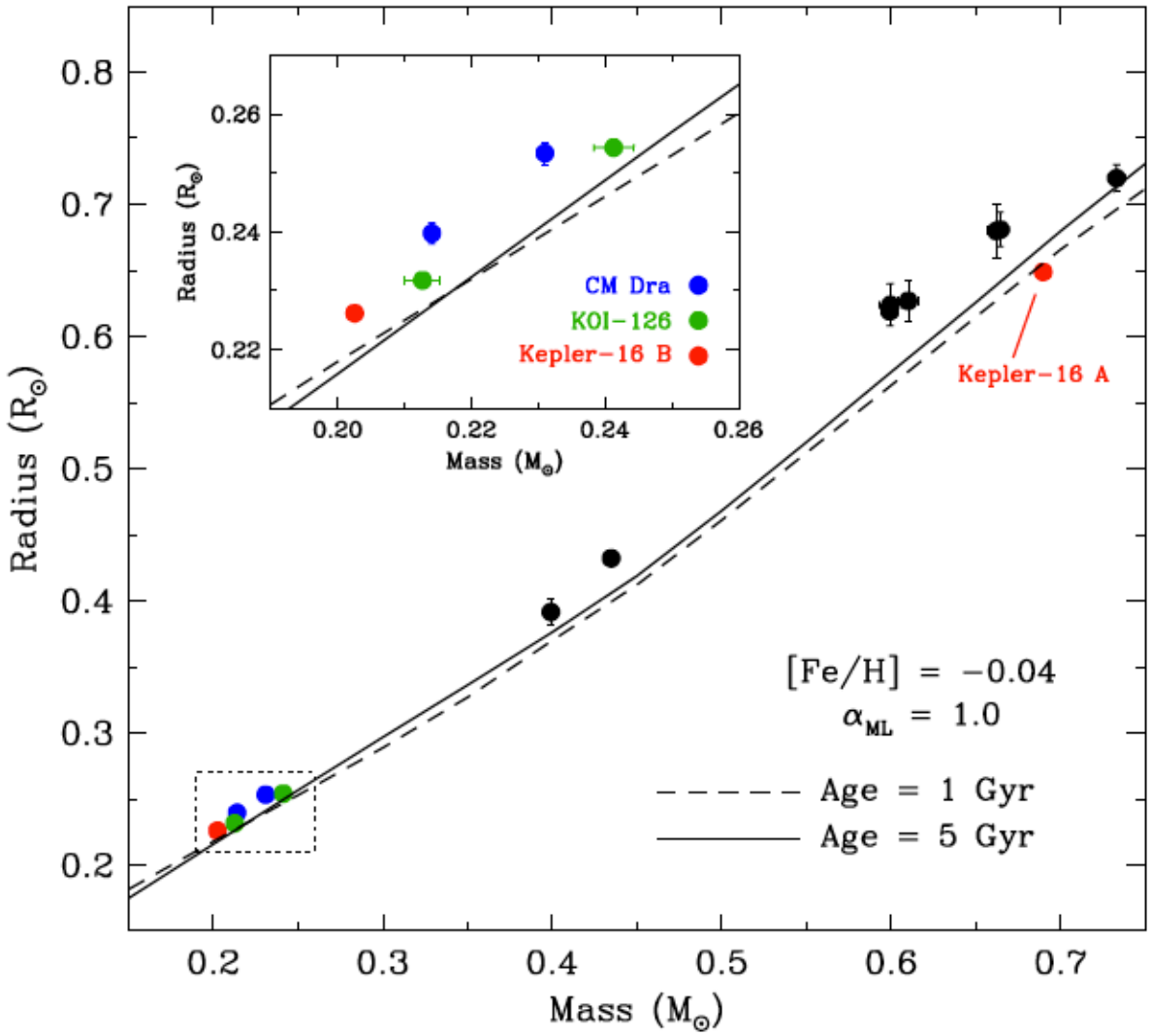
~1 minute scale → ~1 M_{Saturn} / M_{Sun}


Star A
Star B
Radial Velocity [km s^{-1}]
20
0
−20
−40
−60
−80
Residuals [m s^{-1}]
60
40
20
0
−20
−40
−60
0.0
0.2
0.4
0.6
0.8
1.0
Orbital Phase

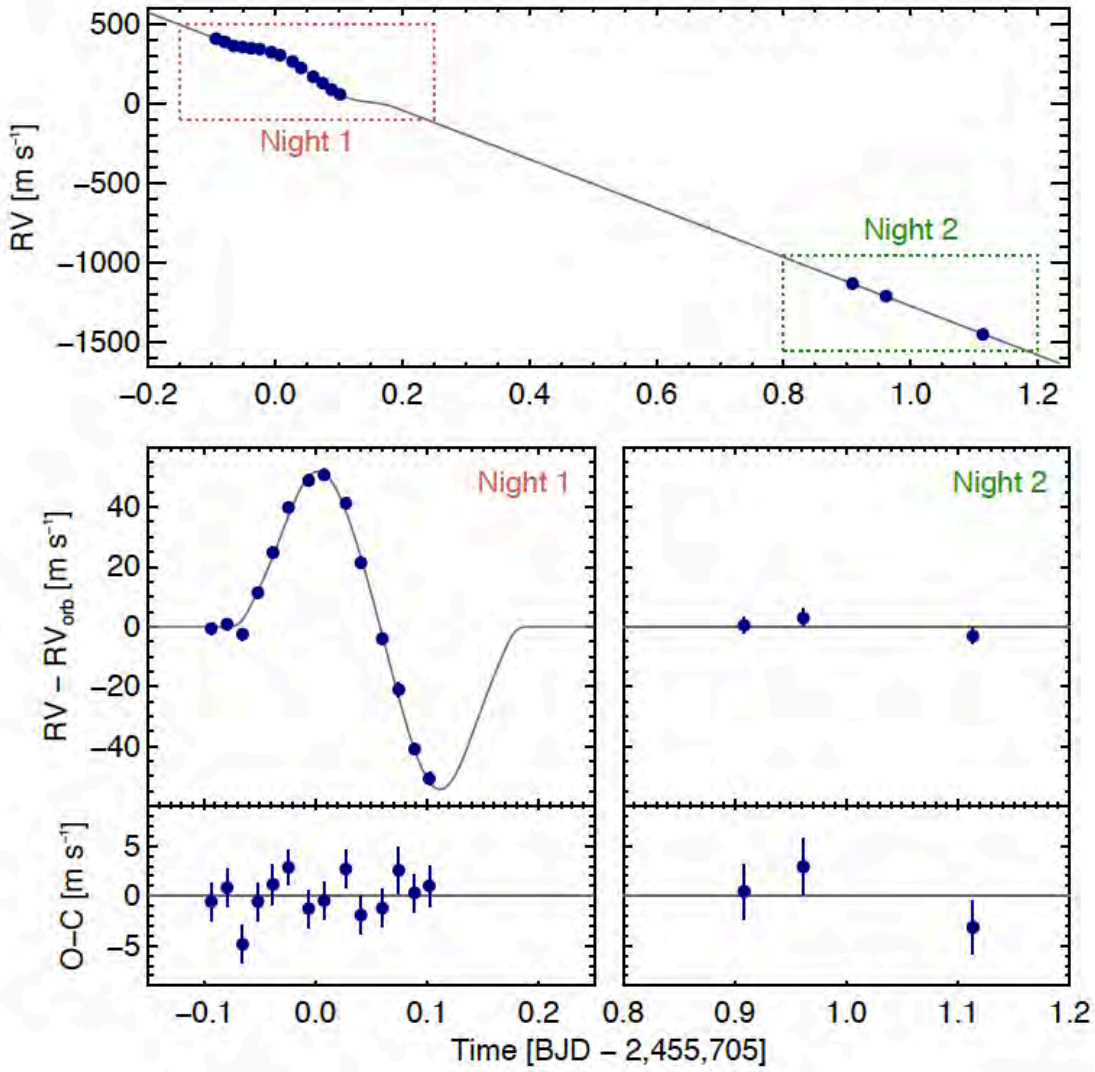
Accurate Masses and Radii

Parameter	Value and Uncertainty
Star A	
Mass, M_A ($M_\odot$)	$0.6897^{+0.0035}_{-0.0034}$
Radius, R_A ($R_\odot$)	$0.6489^{+0.0013}_{-0.0013}$
Mean Density, ρ_A (g cm^{-3})	$3.563^{+0.017}_{-0.016}$
Surface Gravity, $\log g_A$ (cgs)	$4.6527^{+0.0017}_{-0.0016}$
Effective Temperature, $T_{\rm eff}$ (K)	4450 ± 150
Metallicity, [m/H]	-0.3 ± 0.2
Star B	
Mass, M_B ($M_\odot$)	$0.20255^{+0.00066}_{-0.00065}$
Radius, R_B ($R_\odot$)	$0.22623^{+0.00059}_{-0.00053}$
Mean Density, ρ_B (g cm^{-3})	$24.69^{+0.13}_{-0.15}$
Surface Gravity, $\log g_B$ (cgs)	$5.0358^{+0.0014}_{-0.0017}$
Planet b	
Mass, M_b ($M_{\rm Jupiter}$)	$0.333^{+0.016}_{-0.016}$
Radius, R_b ($R_{\rm Jupiter}$)	$0.7538^{+0.0026}_{-0.0023}$
Mean Density, ρ_b (g cm^{-3})	$0.964^{+0.047}_{-0.046}$
Surface Gravity, g_b (m s^{-2})	$14.52^{+0.70}_{-0.69}$

0.50%
0.20%
0.33%
0.26%
4.8%
0.34%


Radius (R⊙)
Mass (M⊙)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
[Fe/H] = −0.04
α_ML = 1.0
Age = 1 Gyr
Age = 5 Gyr
Kepler−16 A
CM Dra
KOI−126
Kepler−16 B
0.20
0.22
0.24
0.26

and that's not all…



Winn et al.
Spin-orbit measurement:
$\lambda = 1.6° \pm 2.4°$

New Views of Exoplanets from *Kepler*

Precision period ratios of transiting planets

- Information on migration at an early epoch

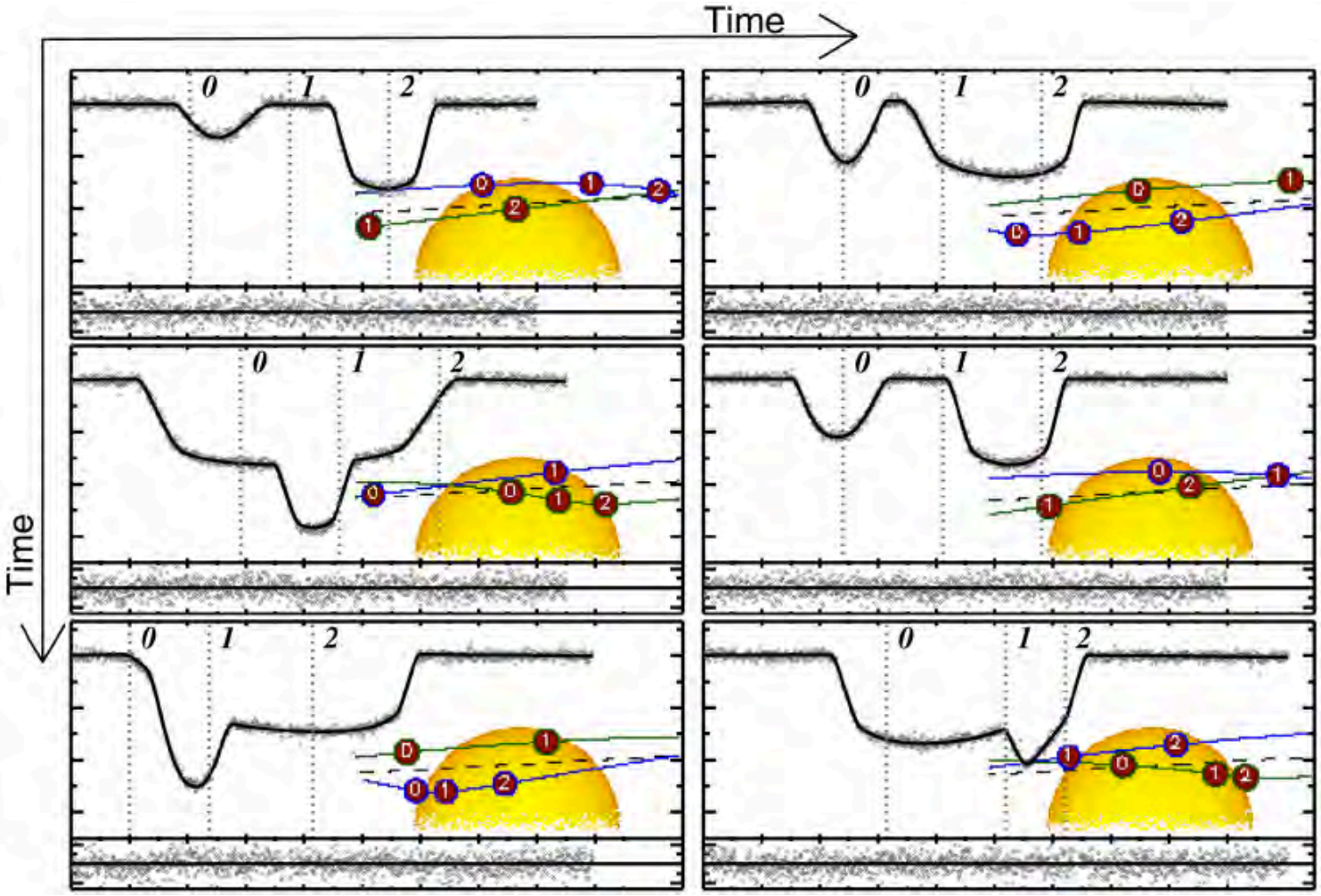
Timing Variations of transiting planets

- Nails down the properties of multiply-eclipsing systems
- The best hope for confirming habitable planets

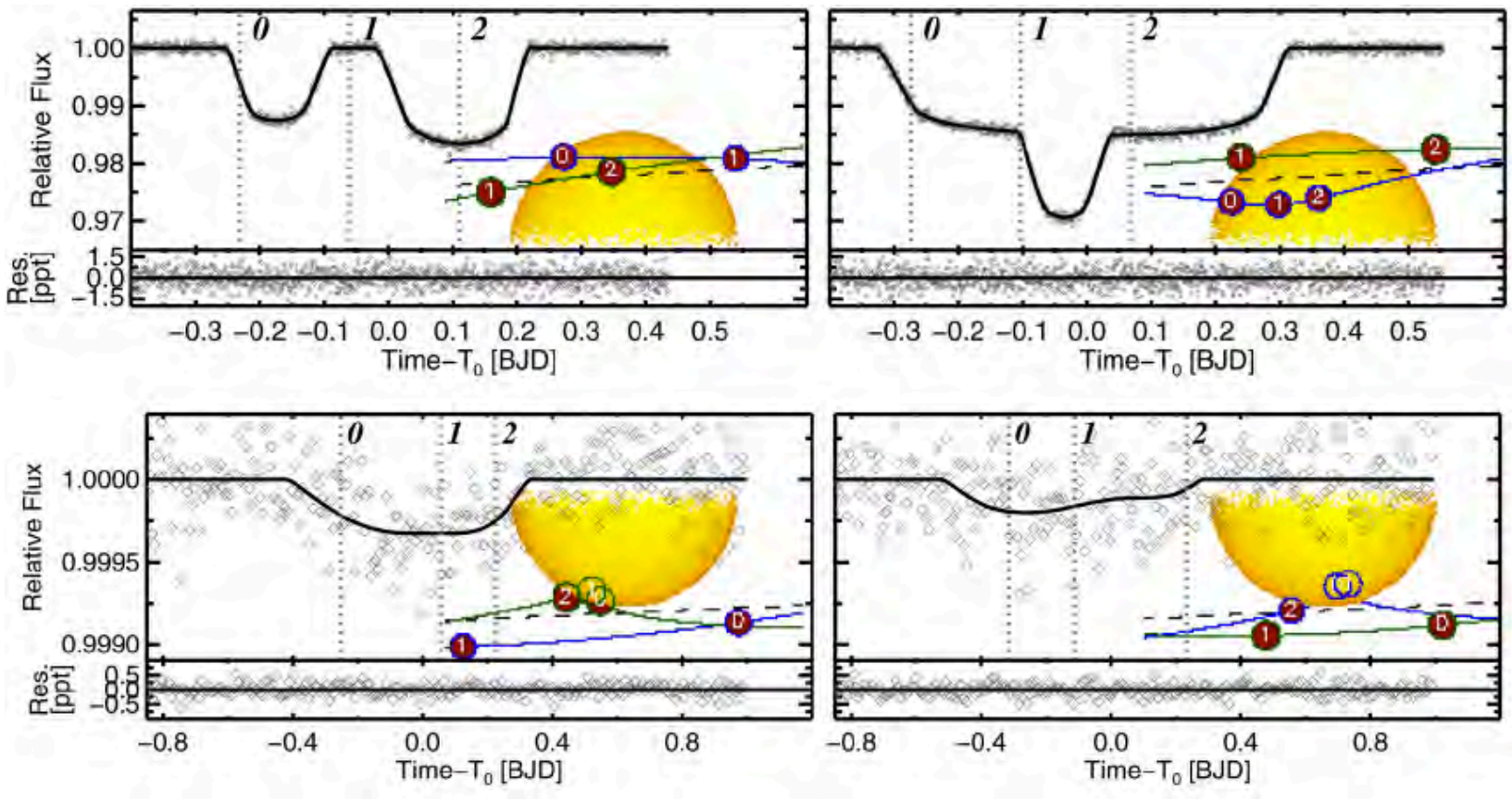
Planets *around* binaries

- First solid detection: a transiting example

KOI-126: A Triply Eclipsing Hierarchical Triple with Two Low-Mass Stars



Carter, Fabrycky, Ragozzine et al. 2011, Science



P_1 = 1.77 d, P_2 = 33.9 d

i_{mutual} =9.2^o, oscillating by 0.4^o